TAMPEREEN TEKNILLINEN YLIOPISTO

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LONG-TERM DEVELOPMENT PLAN FOR REGIONAL NETWORK OF VATTENFALL VERKKO OY

Master of Science Thesis

Examiner: Professor Pekka Verho
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ABSTRACT

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The purpose of the development plan for regional networks is to have a clear picture about the present regional network, change factors and the effects they have on the regional network. The development plan of the regional network has been divided into three study areas; Northern Ostrobothnia, Central Finland and Häme and Pirkanmaa.

This thesis contains information about each areas load growth, the development plan of the main grid and possible production plans, especially, wind power production. This information was gathered from network planners, project managers and wind power producers. Furthermore, the present electrical and mechanical state of the regional network was investigated from information contained by the network information system.

This thesis presents change factors in each study area, changes they will have on regional network and some solutions how to prepare to those changes. All the plans made will be in general level; more detailed plans can be created based on these general guidelines.

The biggest change factors are 220 kV power lines of the main grid changing into 110 kV use in Central Finland and Northern Ostrobothnia and also wind farms increase in Northern Ostrobothnia. The increase in 110 kV power lines makes the building of the new connections and substations possible. This thesis presents two alternative solutions for the longest Koivisto – Nivala power line and compares them. Furthermore, wind power projects are examined in three different scenarios and are created for wind power networks at basic level.

In the future, the ageing power lines of the regional network will be a matter which must be followed carefully. The 50 % of the power lines (500 km) was built in the 1960's and the 1970's. This means that most of the power lines will be reconstructed during the next 15…20 years when the lifetime assumed to be 50…60 years. Therefore, the mechanical condition of the oldest power lines must be more paid attention over the coming years in order to the reconstruction needs of the power line would come into the open well in advance.

TIIVISTELMÄ

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Alueverkon kehityssuunnitelman tavoitteena on saada mahdollisimman kattava kuva nykyhetken alueverkosta, verkkoon vaikuttavista muutostekijöistä ja niiden aiheuttamista muutoksista alueverkkoon. Alueverkon tarkastelu on jaettu kolmeen alueeseen; Pohjois-Pohjanmaa, Keski-Suomi ja Häme ja Pirkanmaa.

Työhön on koottu tietoa jokaisen alueen kuormituksien kasvusta, kantaverkon kehityssuunnitelmista sekä mahdollisista tuotannon suunnitelmista, etenkin tuulivoimasta. Tietoja alueiden muutostekijöistä on saatu verkostosuunnittelijoilta, projektipäälliköiltä sekä tuulivoimayhtiöiltä. Lisäksi on tutkittu verkkotietojärjestelmän tietojen avulla nykyverkon mekaaninen sekä sähkötekninen kunto.

Työssä esitellään alueen muutostekijät, niiden aiheuttamat muutokset sekä joitain ratkaisumalleja, joilla muutoksiin voidaan varautua. Yksityiskohtaisia suunnitelmia ei esitellä vaan tarjotaan suurpiirteisiä ratkaisumalleja, joiden perusteella tarkempi suunnittelu voidaan tulevaisuudessa tehdä.

Suurimmat muutostekijät ovat kantaverkon 220 kV johtojen muuttuminen 110 kV käyttöön Keski-Suomessa ja Pohjois-Pohjanmaalla sekä tuulipuistojen lisääntyminen Pohjois-Pohjanmaan alueella. Kantaverkon 110 kV johtojen lisääntyminen mahdollistaa uusien yhteyksien ja sähköasemien rakentamisen. Työssä on tutkittu kahta vaihtoehtoista ratkaisua pisimmälle Koivisto – Nivala johdolle ja selvitetty niiden toteutusmahdollisuuksia. Tuulivoimahankkeita on tarkasteltu kolmella eri skenaariolla ja luotu niille hyvin karkealla tasolla tuulivoimaverkot.

Tulevaisuudessa alueverkon ikääntyvät voimajohdot nousevat tarkkaan seurattavaksi asiaksi. Alueverkon 110 kV voimajohdoista noin 50 % (500 km) on rakennettu 1960- ja 1970-luvulla. Tämä tarkoittaa, että voimajohtojen 50…60 vuoden eliniällä suurin osa johdoista tulee saneerata seuraavan 15..20 vuoden aikana. Vanhimpien voimajohtojen mekaaniseen kuntoon tuleekin kiinnittää tulevien vuosien aikana tarkempaa huomiota, jotta johtojen saneeraustarve tulisi ilmi riittävän ajoissa.

PREFACE

The topic for this thesis was provided by Vattenfall Verkko Oy. The thesis was examined by Professor Pekka Verho from Tampere University of Technology. The supervisor from Vattenfall Verkko Oy was M.Sc. Turo Ihonen.

I wish to thank Turo for providing me such an interesting and current topic as well as kind suppot during the work. Furthermore, I wish to thank Pekka for good advice and for examining this thesis. As well, I want express my gratitude to everyone who helped me during the work. Special thanks go to my nice fellow members of the Substation and Power lines -team for support. Above all, I acknowledge heartfelt thanks to my family for the valuable support throughout my studies.

Tampere, August 29th, 2011

Tomi Mäkelä

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ABBREVIATIONS AND NOTATION

$\underline{I}_{bus}$	Current matrix
$\underline{I}_{f}$	Earth fault current
$\underline{I}_{k3}$	Three phase short-circuit current
$\underline{I}_{k}$	Two phase short-circuit current
S_{n}	The nominal power
$\underline{U}_{bus}$	Voltage matrix
$\underline{U}_{0}$	The zero sequence voltage
$\underline{U}_{1}$	The positive sequence voltage
$\underline{U}_{2}$	The negative sequence voltage
$\underline{U}_{A}$	Phase-to-earth voltage phasor in A phase
$\underline{U}_{B}$	Phase-to-earth voltage phasor in B phase
$\underline{U}_{C}$	Phase-to-earth voltage phasor in C phase
U_{n}	The nominal voltage
$\underline{Z}_{0}$	The zero sequence network impedance
$\underline{Z}_{1}$	The positive sequence network impedance
$\underline{Z}_{2}$	The negative sequence network impedance
$\underline{Z}_{f}$	The fault impedance
$\underline{Z}_{th}$	The Thevenin’s impedance
$\underline{Y}_{bus}$	Impedance matrix

DSO	Distribution System Operator
EIA	Environmental Impact Assessment
ELY-centre	Centre for Economic Development, Transport and the Environment
EMV	The Energy Market Authory
FINGRID	The main grid operator in Finland
MEE	Ministry of Employment and the Economy (in Finland)
RNO	Regional Network Operator
TSO	Transmission System Operator
VFV	Vattenfall Verkko Oy

1. INTRODUCTION

The purpose of this thesis is to create a development plan for 110 kV regional network of Vattenfall Verkko Ltd (VFV). The aim of the development plan is to evaluate future investment needs and schedule them for the next fifteen years from the present, in other words, about until the year 2025.

The analysis of the regional network is divided into three areas; Northern Ostrobothnia, Central Finland and Häme and Pirkanmaa. The present state of the network, the change factors and possible measures are determined in every area. Exact plans are not made rather the purpose is to create guidelines according to which the regional network will be developed the coming years.

At the first stage of this thesis, the regional network operation and basic principles of the network planning will be briefly defined. At the second stage, the present state of the regional network will be determined and the possible problem sections are identified. As the present state of the regional network is determined, the age distribution and mechanical condition of power lines will first be examined. Furthermore, the loading of the main transformers and the backup feeding of the substations are defined on the basis of the information and calculation of the network information system.

At the third stage of the thesis, the change factors of areas will be defined. The load growth, the regional development plans of the main grid and increasing production, especially a wind power, are examined as the most important change factors.

In the last part of the thesis, most important and most probable change targets are identified. Furthermore, basic plans are created which can be used to prepare for future changes. It is not intended to create exact network plans instead presents solutions.

2. REGIONAL NETWORKS IN FINLAND

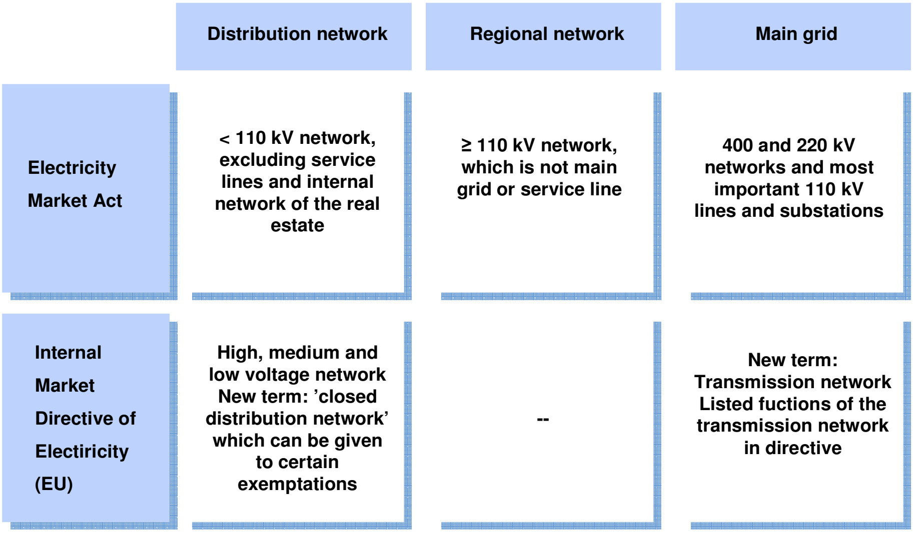
2.1. Definition of the regional network

In the electricity market act, only the distribution network has been exactly defined. The distribution network is a power network with a nominal voltage of less than the 110 kilovolts (kV). The geographical area of responsibilities has been determined for the distribution network operators (DSOs) where the DSOs have connecting obligation of network, the transfer obligation of electricity and the development obligation of network. DSOs have an exclusive right to build the distribution network in own area of responsibilities excluding service lines and the internal network of real estate.

According to the reason of electricity market act, the bigger voltage network than the distribution network is the main grid or the regional network. In the reasons, it has been stated that the main grid includes 400 kV and 220 kV networks and most important 110 kV power lines and substations. The regional network operation can be carried on either as a separate business, alongside the main grid operation, however, separately from actual the main grid operation or as a part of distribution network operation. All operation models are used in Finland. [1]

The new internal market directive of the electricity was given in July 2009. The directive has to be valid in national legislation in March 2011. The most significant changes in the directive apply to the securing of the independence of the transmission network operators (TSOs, the main grid company) and the regulators' tasks and competence. In addition, the directive identifies four models of network operators: TSO, DSO, their combination and closed distribution network. The regional network term is not found in the directive as it did not exist either in the earlier directive. Table 2.1 shows the summary of the network defining in the legislation.

Table 2.1 Summary of the network defining in legislation. [3]



	Distribution network	Regional network	Main grid
Electricity Market Act	< 110 kV network, excluding service lines and internal network of the real estate	≥ 110 kV network, which is not main grid or service line	400 and 220 kV networks and most important 110 kV lines and substations
Internal Market Directive of Electricity (EU)	High, medium and low voltage network New term: ’closed distribution network’ which can be given to certain exemptations	--	New term: Transmission network Listed fuctions of the transmission network in directive

According to the directive, the TSO is an operator which is responsible for the use, maintenance and developing of the transmission network. Correspondingly, the DSO is an operator which is responsible for use, maintenance and developing of the distribution network. Transmission means “the transport of electricity on the extra high-voltage and high-voltage interconnected system with a view to its delivery to final customers or to distributors, but not including supply”.[2] The distribution means, “the transport of electricity on high-voltage, medium voltage and low voltage distribution systems with a view to its delivery to customers, but not including supply”.[2] Criteria has not been defined in more detail for separating of the transmission network and the distribution network from each other in the directive. The network is defined as the closed distribution network where is transferred electricity in geographically limited industrial area. The closed distribution networks can be absolved from the obligation to acquire the loss energy with market based procedures and having the tariffs approved on the authority. [3]

2.2. Regional network operation

The 110 kV power lines are classified as the regional networks in Finland’s electricity market which do not belong to the main grid. The business of the regional network is organized in different ways depending on is the owner of the regional network a DSO, industrial enterprise or regional network operator (RNO). At this moment, RNOs are 12 companies and DSOs are 55 companies which own the 110 kV power lines. In the regulation model of the network operation, the 110 kV power lines owned by DSO are included other network if the regional network operation has not been corporatized to a separate company.

The regional network owned by industrial enterprise is usually used as a service line which means that other customers have not connected to the network. In addition, network operation has been organized in a separate company.

The 110 kV networks of RNOs and DSOs vary from a few kilometers to over a thousand kilometers. One RNO also owns 400 kV power line. This power line was originally built for service line to the main grid. Nowadays, the power line has been connected with other customers so the meaning of connection has changed from the original. The 110 kV network lengths of RNOs are shown in Table 2.2. In addition, the table shows five DSOs which have the most 110 kV network from other DSOs. [3]

Table 2.2 *The 110 kV network lengths of RNOs and five DSOs (year 2009). [4]*

Regional network operators	
Company	**Network 110 kV (km)**
EPV Alueverkko Oy	**703,4**
Kittilän Alueverkko Oy	**207,5**
Lapin Sähköverkko Oy	**192,7**
Sähkö-Virkeät Oy	**188**
UPM Sähkönsiirto Oy	**109,2**
PVO-Alueverkot Oy	**102,2**
Satavakka Oy	**83**
Satapirkan Sähkö Oy	**47,8**
Enso Alueverkko Oy	**41,2**
Porvoon Alueverkko Oy	**30**
Äänevekko Oy	**4,6**
Mäntän Energia Oy	**4,5**
Distribution network operators	
Company	**Network 110 kV (km)**
Fortum Sähkönsiirto Oy	**1731,6**
Vattenfall Verkko Oy	**1025,9**
Savon Voima Verkko Oy	**503**
Järvi-Suomen Energia Oy	**401**
Herrfors Nät-Verkko Oy Ab	**301,7**

RNOs and DSOs own altogether about 8120 km of the 110 kV network. Furhermore, the main grid operator (Fingrid) manages approximately 7500 km of 110 kV network. This means that VFV owns 6,5 % of the Finland’s whole 110 kV network.

3. THEORY OF NETWORK PLANNING

3.1. Overall philosophy

The purpose of the network planning is to secure the adequacy and reliability of the network. The reliability means that the most usual network faults must not cause interruption in electricity delivery. The task of the network planning is to clarify the necessary confirmations and investments. The transmission and distribution are economical if the network planning is carefully made. Particularly, the economy must be kept in mind when the network is planned. The unnecessary investments have to be avoided for the reason that the network investments are generally expensive.

The network planning is generally divided into two parts: short term planning, in other words, target planning which time period is less than five years. The long-term plans will be made for 5…15 time period. Furthermore, the so-called over long-term plans can be formulated to the time period of 15…30 years.

The network planning is made mainly with calculatory methods. In which case, the information about the components of the network such as loads, power lines, transformers and generators are needed for calculations. [5]

3.2. Technical requirements

Network planning requires knowledge of the existing electrical network to provide a firm base on which to assess projects for future network development. Technical requirements such as those which can influence future loads need to be considered.

The most important technical requirements are load flow and fault current calculations in the network planning of the regional network. This means, on the basis of the load flow calculation is estimated losses, voltages and production and consumption of the active and reactive power. Correspondingly, on the basis of the fault current calculation is clarified fault currents at the point of the fault and values of fault current at other points on the network. [5]

3.2.1. Load flow

The purpose of load flow calculation is to clarify voltages, currents and active and reactive power of all buses of the network. The bus has been defined when its voltage magnitude (U), phase angle (φ), active power (P) and reactive power (Q) is known. The powers mean net powers, in the other words, production reduced by consumption. The buses are divided into types in the calculations on the basis of which of four variables are known. [6; 8]

Net active and reactive powers are known from PQ-buses. The unknowns are voltage magnitude and phase angle which means that they must be calculated. PQ-buses describe a load bus or such generator bus where the generator works with constant reactive power control.

Net active power and voltage magnitude are known from PU-buses which mean that phase angle and reactive power must be calculated. PU-buses are always generator buses where the generator works with constant voltage control.

Voltage magnitude and phase angle are specified from Uφ-bus and active and reactive powers at this bus are not specified. Normally, there is only one bus of this type in a given network. Uφ-bus is named a slack bus or reference bus. The phase angle of voltage will be defined by way of reference bus. Difference between production and consumption is fed from reference bus. Usually, reference bus describes the background network or generator.

Different variables (U, P, Q) have been generally drawn the lines where they are free to change during the calculation. Furthermore, the positions of the on-load tap changer of the transformers are able to change. Sometimes, the bus type may change if the study regulations are not realized. If the reactive power limit of the generator is exceeded, it changes from the PU-bus to PQ-bus. In load flow calculation, the following equation (1) is formulated for currents and voltages of the network. [8]

$$[\underline{I}_{bus}] = [\underline{Y}_{bus}][\underline{U}_{bus}] \tag{1}$$

Where

$\underline{I}_{bus}$ is the current matrix which includes sums of currents which come to the each buses

$\underline{U}_{bus}$ is the voltage matrix which includes voltages of each buses

$\underline{Y}_{bus}$ is the admittance matrix which includes admittances between buses

Since in a network each bus is connected only to a few other buses, the admittance matrix is very sparse. In other words, it has a large number of zero elements. If the network is large, the direct solution method is slow. Therefore, different iterative methods are used. These kinds of methods are for example Newton-Raphson and Gauss-Seidel.

3.2.2. Fault calculations

The essential part of network planning is analysis of the fault situation. Common faults are short-circuit and tripping of components due to over load. These are usually caused by weather conditions or fault in the network components.

Some of the fault situations are symmetrical, in the other words, three-phases short-circuit faults. However, this is the case only when the fault occurs when the voltage reaches its peak value. Otherwise the three-phase short-circuit fault is asymmetrical.

In symmetrical system, the system impedances in each phase are identical and the three-phase voltages and currents are completely balanced. That means, they have equal magnitudes in each phase and are progressively displaces in time phase by 120 degrees. Thus, the symmetrical three-phase short-circuit current can be calculated with the single-phase eguivalent according to Thevenin's theorem.

$$\underline{I}_{k3} = \frac{\underline{U}_a}{\underline{Z}_{th} + \underline{Z}_f} \tag{2}$$

Where

$\underline{I}_{k3}$ is the three-phase short-circuit current
$\underline{U}_a$ is the phase-to-earth voltage phasor in A phase
$\underline{Z}_{th}$ is the Thevenin's impedance
$\underline{Z}_f$ is the fault impedance

In the equation, Thevenin's impedance $\underline{Z}_{\mathrm{th}}$ represents the total network impedance seen from the fault point. This impedance also contains the impedance of the main grid. In addition to the impedance, there are also other factors that affect the short-circuit current. These are according to the equation (2) the network voltage, the fault type and the loading during the fault although this usually has a minor influence on the fault current. The typical short-circuit fault current values in the 110 kV networks are 10…40 kA in Finland. [7]

The most common asymmetrical faults are a single-phase earth-faults and two-phase short-circuit faults. During these kinds of faults, different phases of voltages and currents are not symmetrical. In calculation, the network cannot be analyzed with the single-phase equivalent which means each phase must be examined separately.

Asymmetric situations are examined with symmetrical components and sequence network. Representing the network with symmetrical components is a mathematical method for network calculation where the phasor coordinates are transformed into sequence coordinates. This is shown in Figure 2.1.

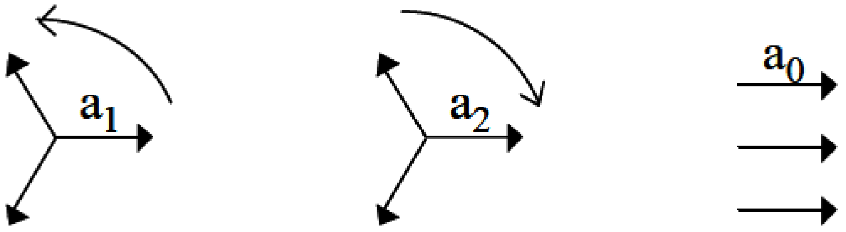


Figure 3.1 *Positive sequence network a_1, negative sequence network a_2 and the zero sequence network a_0.*

Components are called positive sequence network, negative sequence network and the zero sequence network. The idea is that by connecting these sequence phasors, the phasor diagram of the fault can be represented. The asymmetrical phase voltages are thereby formed as a combination of three symmetrical networks.

The transitions from the phase values to symmetrical components and back succeed with conversion matrixes which are presented in equation (3) and (4). [8]

$$\begin{bmatrix} \underline{U}_a \\ \underline{U}_b \\ \underline{U}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \underline{a}^2 & \underline{a} \\ 1 & \underline{a} & \underline{a}^2 \end{bmatrix} \begin{bmatrix} \underline{U}_0 \\ \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \underline{U}_0 \\ \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \end{bmatrix} \begin{bmatrix} \underline{U}_a \\ \underline{U}_b \\ \underline{U}_c \end{bmatrix} \tag{4}$$

Where

$\underline{U}_a$, $\underline{U}_b$ and $\underline{U}_c$ are the phase-to-earth voltages
$\underline{U}_0$, $\underline{U}_1$ and $\underline{U}_2$ are the zero, positive and negative sequence network voltages
$\underline{a}$ is the complex number operator $e^{j120°}$

The impedances can be of different sizes on different component networks. Impedances of the zero sequence network must be known in order to asymmetrical faults can be calculated. The negative sequence network is also needed in two-phase short-circuit faults. The two-phase short-circuit current can be calculated with equation (7). [8]

$$\underline{I}_k = \frac{\sqrt{3}\underline{U}_a}{\underline{Z}_1 + \underline{Z}_2 + \underline{Z}_f} \tag{7}$$

Where

$\underline{I}_k$ is the two-phase short-circuit current
$\underline{Z}_1$ is the positive sequence network impedance
$\underline{Z}_2$ is the negative sequence network impedance

In earth-fault situations, all three component networks are needed and it can be calculated with equation (8).

$$\underline{I}_f = \frac{3\underline{U}_a}{\underline{Z}_0 + \underline{Z}_1 + \underline{Z}_2 + 3\underline{Z}_f} \tag{8}$$

Where

$\underline{I}_f$ is the earth-fault current
$\underline{Z}_0$ is the zero sequence network impedance

3.2.3. Load and fault current capacity

One factor which restricts electricity transmission is a load capacity of network components. The load capacity informs how much current and power can be transferred through the component without being damaged. Temperature rise determines the load capacity exclusively with cables and transformers. The heat develops when a part of the power changes into heat from an effect of the resistance.

On the power lines, a more significant factor is a short-circuit current because power lines are not insulated and ambient temperature cools them effectively. On cold weather, power can be transferred significantly more than on warm weather. Figure 3.2 shows the load capacity of three conductors as a function of the ambient temperature. Load capacity has been calculated according to IEC 1597 standard.

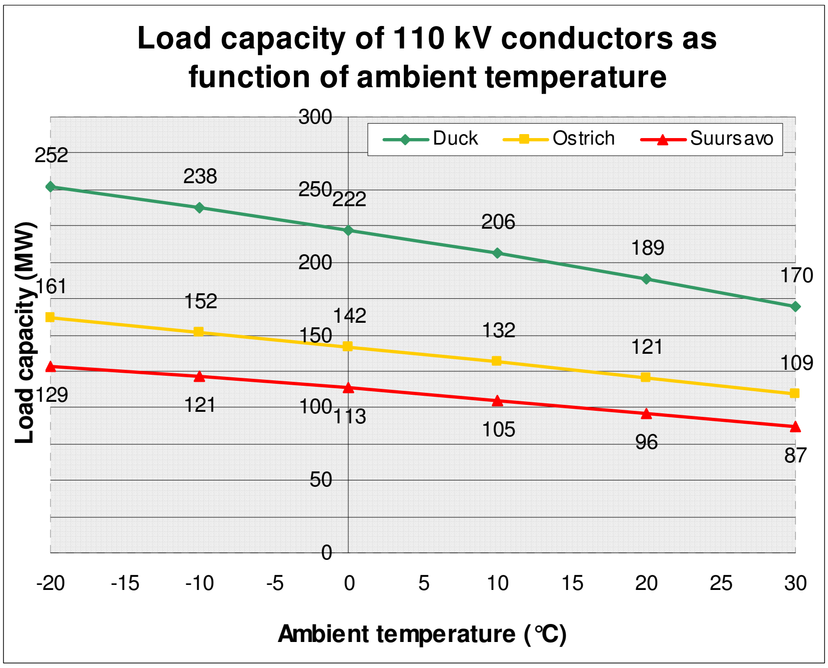


Figure 3.2 Load capacity of 110 kV conductors as function of ambient temperature. Voltage 110 kV, rated temperature of lines 80°C and wind 0,6 m/s.

The conductors that are shown in Figure 3.2 are the most general conductors which are in use in the regional network of Vattenfall Verkko Ltd. The electrical values of conductors are introduced in Table 3.2.

Table 3.1 *Electrical values of 110 kV conductors [9;10]*

Type	Cross-sectional area (aluminium/core) mm^2	Resistance (20°C, DC) Ω/km	Current load capacity A	Short-circuit current (1s, 200°C) kA
Suursavo	106 / 25	0,273	429	11,2
Ostrich	152 / 25	0,19	537	15,9
Duck	305 / 39	0,095	837	31,6
2-Duck	-	0,048	1280	-

The transformers are well protected from the excessive temperature rise by efficient cooling and protection devices. In the abnormal situations, such as the backup feeding of the substation, the temporary overload can be allowed ($1,2*S_n$). Excessive temperature rise can damage the insulation of the transformer and other structures during the long. During the lifetime, peak load situations stress transformers and may shorten their lifespan. Therefore, the load growth must be taken into consideration at the planning stage in order to components last out their lifespan. Undersized power lines and transformers have to be changed before one's time which increases unnecessary costs.

3.3. Reliability

The fault situations of the regional network are usually caused by the environmental conditions as overvoltage due to lightening. The faults caused by the lightening are short-term short-circuit faults and earth-faults which can be removed with reconnection.

In the regional networks, the permanent faults are extremely rare. The falling of the pole or the falling of the overlong tree to the power line are the most general reasons for the permanent faults. The falling of the pole usually is caused by the breaking of stay wires.

The falling of overlong trees is prevented by clearing the right-of-way wide enough. Furthermore, border zone next to the right-of-way is kept 10 m high. The Figure 3.2 shows the right-of-way and border zones.

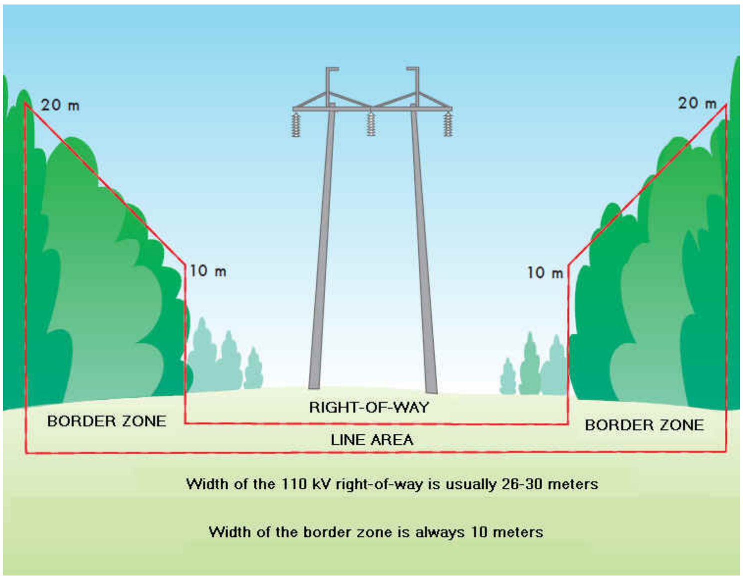


Figure 3.2 *Right-of-way and border zones.[11]*

The fault interruptions consist of short-term interruptions or long-term interruptions. According to IEEE 1366 standard reliability of delivery can be described with key figures introduced below

System Average Interruption Duration Index (SAIDI):

$$SAIDI = \frac{\sum_i \sum_j t_{ij}}{N_s} \tag{9}$$

System Average Interruption Frequency Index (SAIFI)

$$SAIFI = \frac{\sum_j n_j}{N_s} \tag{10}$$

Customer Average Interruption Duration Index (CAIDI):

$$CAIDI = \frac{\sum_i \sum_j t_{ij}}{\sum_j n_j} = \frac{SAIDI}{SAIFI} \tag{11}$$

Where

n_j is the number of the customers who experience the interruption i
N_s is the total amount of customers
T_{ij} is the time without electricity that customers j have to spend because of the interruptions i

In these equations the momentary interruptions, i.e. outages lasting three minutes or less, are taken into consideration. This is why the MAIFI figure is used to measure the short-term interruptions per customer. [8]

Momentary Average Interruption Frequency Index (MAIFI)

$$MAIFI = \frac{TotalNumberOfMomentaryInterruptions}{TotalNumberOfCustomers} \tag{12}$$

Table 3.2 presents the fault numbers and fault frequencies of 132 kV power lines in the Nordic countries in 2007. In addition, the table shows the division of faults according to cause during the years 1998-2007. As from the table one can see, nearly half of the faults are caused by the lightning in Finland. Furthermore, permanent faults are only 2 % of all faults, in other words, 0.3 faults per 1000 km.

Table 3.2 *Division of faults according to cause for 132 kV power lines.[12]*

Country	Line km 2007	Num-ber of faults 2007	Number of faults per 100 km		Faults divided by cause during the period 1998-2007 (%)								
			2007	1998-2007	Light-ning	Other natural causes	Ex-ternal influ-ences	Ope-ration and mainte-nance	Tech-nical equip-ment	Oth-er	Un-known	1-pha-se faults	Perma-nent faults
Denmark	3640	60	1.65	1.23	21.7	48.9	16.7	2.4	1.2	3.2	6.0	47	5
Finland	13991	181	1.29	1.92	44.2	3.9	2.1	1.3	0.5	0.9	47.1	75	2
Iceland	1247	12	0.96	1.49	2.2	86.1	3.4	1.1	6.6	0.0	0.5	47	14
Norway*	10475	56	0.53	1.05	57.2	27.7	3.4	0.6	6.1	4.1	0.9	26*	17
Sweden	15418	197	1.28	2.42	63.2	4.4	2.8	1.9	1.9	1.9	24.0	42	5
Nordel	44771	506	1.13	1.77	52.1	13.4	3.7	1.5	2.2	2.0	25.0	50	6

*The Norwegian grid partly includes a resonant earthed system, which has an effect on the low number of single phase earth faults in Norway.

3.4. Economic efficiency

In the planning of the network, the aim is to find a solution which functions technically and the total costs are small in the long-term. Costs can be on-off, annual or variable. Furthermore, costs must be specified from each other so that the total costs can be compared. The division into the separate cost factors can be made according to the following equation:

$$C_{tot} = C_{inv} + C_{loss} + C_i + C_m \tag{13}$$

Where

C_{tot} is the total cost
C_{inv} is the investment cost
C_{loss} is the loss cost
C_i is the interruption cost
C_m is the maintenance cost

The investment costs make up a large part of the total costs in the building of the regional network. The investment costs include material, building and land-use costs. The loss costs include the load loss of the network and the no-load loss of the transformers. The interruption costs contain the reliability costs. The maintenance costs comprise the costs which result from the maintenance and inspection of the network.

The investment costs are usually on-off and they realize at the first stage of the lifetime of the network. The loss, interruption and maintenance costs are annual and remain constants or change yearly. Two methods can be used when different network alternatives are compared, present value method or annuity method. [13]

3.4.1. Present value method

Amount of money is calculated with the present value method which now would be needed for amortize the lifetime costs of the network. In the other word, talking about the discounted costs where the length of the observation period, the interest rate of money and the load growth have been taken into consideration. The discounting is made with the capitalization coefficient by multiply the costs of the first year.

$$C_{tot} = k * C_0 \tag{14}$$

Where

C_{tot} is the total cost
C_0 is the cost of the first year
K is the capitalization coefficient

If the variable costs are constant every year, as maintenance costs, coefficient consists of only the length of the observation period and the interest rate of the money.

$$k = \psi \frac{\psi^T - 1}{\psi - 1} \tag{15}$$

$$\psi = \frac{1}{\alpha} = \frac{1}{1 + p/100} \tag{16}$$

Where

T is the observation period
p is the money rate

As loss cost is calculated, it must be taken into consideration that load and losses are not necessarily constants but they vary every year. In the situations, where the load growth can be estimated according to certain per cent, the calculation of the capitalization coefficient changes as follows.

$$\psi = \frac{\beta^2}{\alpha} = \frac{(1 + r/100)^2}{1 + p/100} \tag{17}$$

Where

r is the growth percentage of the power

From the equation, it is noticed that the growth of power increases losses quadratically. If the power is assumed to be constant, the equation (16) can be used. The transformer loss calculation is a good example the use of equations where losses have to specify differing no-load and load losses. The no-load losses do not depend on the load but they will be equal during everyone's hour of the year, whereas, load losses change according to the consumption. [13]

3.4.2. Annuity method

The profitability of the investments can not be compared if their lifetimes differ. In that case, the annuity method will be used when the total costs of alternatives are changed into annual level. The calculation is performed with the annuity coefficient in which case the amount of annuity is obtained by multiply the investment costs on the annuity coefficient. [13]

$$C_{an} = \varepsilon * C_{inv} \tag{18}$$

$$\varepsilon = \frac{p/100}{1 - \frac{1}{(1 + p/100)^T}} \tag{19}$$

Where

C_{an} is the annual payment

ε is the annuity coefficient

3.5. Planning tools

VFV uses the network information system of Tekla Xpower for the planning of the medium and low voltage network. Furthermore, VFV has a licence to PSS/E software whereby the transmission and the regional network can be calculated.

The starting point for this work is to model the regional network with the PSS/E software in order to more exact electrotechnical examinations can be made for the regional network. With Tekla Xpower is calculated the loads of the main transformer. In the following chapters, the properties of Tekla Xpower and PSS/E have been presented briefly.

3.5.1. Tekla Xpower

Xpower is the network information system developed by Tekla Plc. The user interface is graphic and contains the menus and tool bars which are typical of the Windows programs. The mains supply is presented graphically drawn over the background map. Xpower creates the network topology directly which is grounded on the location of network components.

The program makes possible to optimize the different connection situations and building projects of the network both technically and economically. The Construction Project Planning (CPP) application supports network planning by allowing the user to create a network construction plan, including material and work costs. The Power System Analysis (PSA) application is used to perform various network calculations for both current and future network setups, such as load flow, short-circuit and earth-fault calculations. [14]

3.5.2. PSS/E

PSS/E is software which can be used to simulate a power system in both continuing and changing state. PSS/E can be used for the load flow calculation, for the fault analysis, for the forming of the equivalent and for the dynamics simulations of the network.

In this thesis, PSS/E is used for the load flow calculation in normal and backup feeding situations. The main grid company is asked, if necessary, to calculate the values of the short circuit currents.

In PSS/E, there is three Newton-Raphson and two Gauss-Seidel solution methods for the calculation of the load flow. Gauss-Seidel methods function better than Newton-Raphson methods in the situation in which the initial values of voltages are removed from real values. On the other hand, Gauss-Seidel methods do not react well to the series capacitances so the most useful of the solution methods are Newton-Raphson methods which also are used in this thesis. [15]

4. THE PRESENT STATE OF THE REGIONAL NETWORK

4.1. General

Vattenfall Verkko Ltd (VFV) is responsible for 395 000 customers' power network services in the area of more than a hundred municipalities in Häme, Pirkanmaa, Central Finland and Ostrobothnia. VFV has about 62 000 km of electrical network whereof about 1400 km is the regional network including power lines 110 kV and 45 kV. In this thesis, 110 kV network is only examined for the reason that the development plan of 45 kV regional network has been made Toivo Nivala's thesis in the year 2009. [16]

Vattenfall's regional network

Power lines	
Voltage level	Length (km)
110 kV	1026
45 kV	409

Substations	
Substation type	Amount
110/20 kV	119
45/20 kV	16

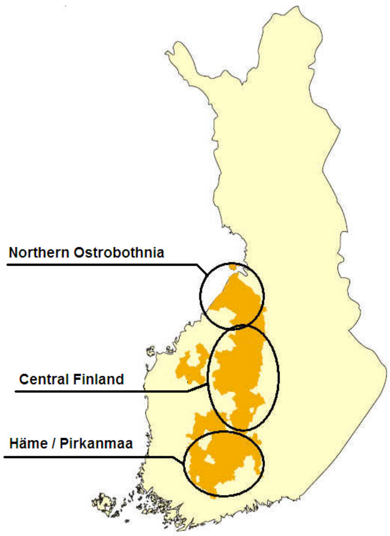


Figure 4.1 Key ratios of the regional network and the territory in the year 2010.

Figure 4.1 shows the line length of the regional network and the number of the substations in the year 2010. There are 1026 km of 110 kV network and 409 km of 45 kV network. Furthermore, there are 135 substations in total whereof 119 are 110/20 kV substations. The figure also shows the territory of VFV with an orange color, which extends from Karkkila to Hailuoto in the south and northern direction and from Lapua to Heinola in the west and east direction. The analysis of the regional network has been divided into three study area; Northern Ostrobothnia, Central Finland and Häme/Pirkanmaa.

4.2. Northern Ostrobothnia

A third of the 110 kV network is located in the Northern Ostrobothnia. The total length of the network is about 330 km and it is divided into six different length power lines. The power lines feed fifteen substations in total including 45/20 kV substations. All in all, there are 21 substations from which six 110/20 kV substations have been connected to the main grid directly.

The regional network of Northern Ostrobothnia and the main grid are shown in Figure 4.2. The substations of VFV are illustrated with red circles and the substations of Fingrid with yellow circles. The 110 kV and 45 kV power lines of VFV are shown with black and light blue lines. Correspondingly, the 110 kV and 220 kV power lines of Fingrid are shown with red and green lines

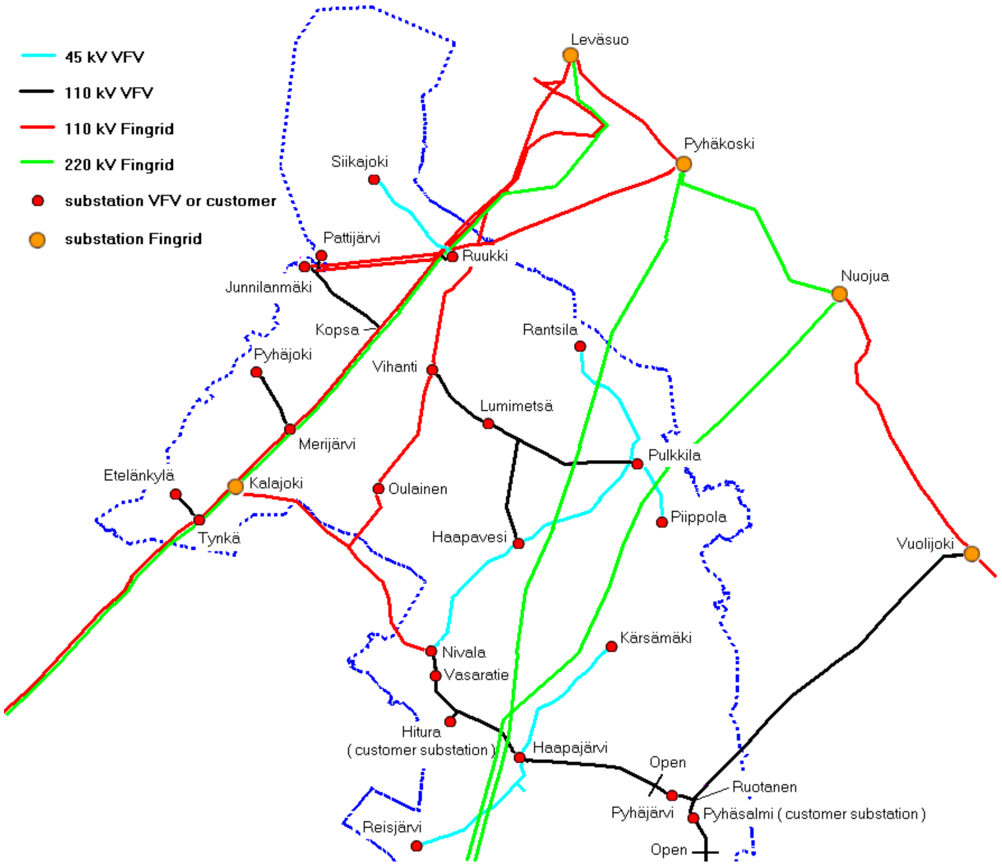


***Figure 4.2** Regional network of Northern Ostrobothnia.*

The 110 kV power lines of coast area have been connected to the main grid in Ruukki, Kopsa, Merijärvi and Tynkä. In the middle part of Northern Ostrobothnia, there are connections to the main grid in Vihanti, Nivala and Vuolijoki. The regional network is radially used so that it is fed from Vihanti to Haapavesi and Pulkkila. Furthermore, it is fed from Nivala to Haapajärvi and from Vuolijoki to Pyhäjärvi and Pyhäsalmi. The 110 kV network continues from Pyhäsalmi to Koivisto's substation of the main grid. The 45 kV power lines between Nivala and Pulkkila are backup connections.

4.2.1. Age distribution and mechanical condition of power lines

More than 50 % of the 110 kV power lines (176 km) were built in the 1960's and the 1970's. This means, that more than half of 110 kV power lines should be reconstructed during the next twenty years as the lifetime of 110 kV power lines is assumed to be 50…60 years. However, it is possible to raise the lifetime for 10…20 years by improving the mechanical condition of power lines. The age distribution of 110 kV power lines is introduced in Figure 4.3.

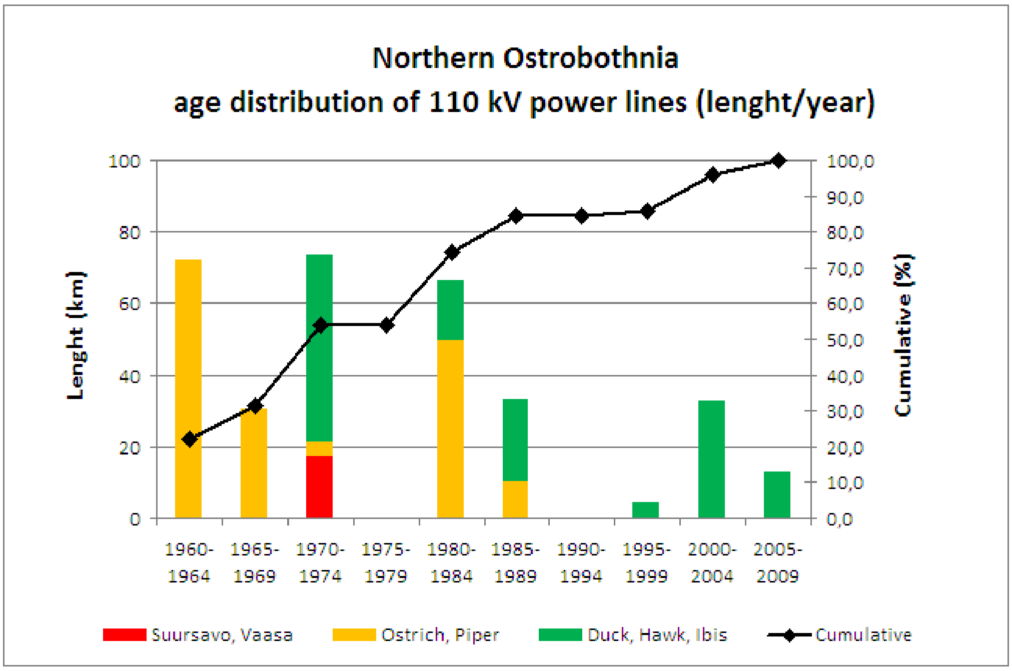


Figure 4.3 *Age distribution of 110 kV power lines according to the conductors.*

About 72 km long Vuolijoki – Ruotanen power line and about 30 km long Nivala – Haapajärvi power line are the oldest power lines of the area. Both power lines were built in the 1960's. These power lines should be reconstructed as the first one due to weak mechanical condition.

Nivala – Haapajärvi power line has been built without concrete foundations. Therefore, some of the poles are askew and rotted from the base. Furthermore, overhead earth wires are missing about 20 km distance. Similarly, 70 % of the foundations of Vuolijoki – Ruotanen power line have weathered and some of the poles have rotted.

In addition to the above power lines, Kopsa – Pattijärvi power line is also mechanically in weak condition. Power line is about 17 km long and it has been built in the year 1970. Some of the poles have rotted and 13 % of the poles are in askew. Kopsa – Pattijärvi power line will be taken out of use within a few years so that the substation of Pattijärvi will be connected to 110 kV power lines of Fingrid (Figure 4.2). The substation of Junnilanmäki was completed in 2010 and it was connected to 110 kV power line of Fingrid at that time.

Other power lines of the area are still in good condition on the basis of the condition inspections that have been done in the years 2008 and 2009. However, a more exact condition inspection would be good to make Pyhäsalmi – Pihtipudas power line after a few years in which case the mechanical condition and lifetime of the power line could be estimated in more detail.

4.2.2. Loading of main transformers

In the area of Northern Ostrobothnia, there are sixteen 110 kV substations and twenty-two 110/20 kV main transformers which nominal powers are about 360 MVA in total. The biggest individual transformers are 25 MVA which are located in Etelänkylä, Haapajärvi, Haapavesi and Vasaratie.

Mainly, two main transformers are on substations which also feed 45 kV power lines. However, two main transformers are also in Junnilanmäki and Pyhäjärvi. The oldest main transformers are located in Junnilanmäki, Merijärvi, Nivala and Pyhäjoki. The main transformers were manufactured at the end of 1960's.

In Appendix 1, the measured and calculated powers of the main transformers have been presented expect for 45/20 kV transformers. The biggest loads of the main transformers (>75 %) are in Etelänkylä, Haapajärvi, Haapavesi and Pulkkila. The main transformers two of Haapajärvi and Pulkkila are almost in a hundred percent loads.

However, it is possible to disengage of the second main transformer of Haapajärvi by changing the connection of the main transformers, in which case, the bigger 25 MVA transformer feeds the loads of the smaller 20 MVA transformer. Also in Pulkkila, the load of transformers can be lightened by changing the connection of the main transformers so that the bigger 16 MVA transformer will feed the loads of the smaller 10 MVA transformer. If the connection of main transformers is changed, the protection arrangements of feeders have to be checked since the short circuit currents can change.

By changing the connection of the main transformers, loads can be lightened rapidly in which case the new transformers do not need to be bought yet. The new transformers will be topical at that stage when the loads of substations increase from the present ones.

4.2.3. Backup feeding of substations

The individual substations are possible to feed via medium voltage network if they are located at the end of a radial power line or they have been connected to the power line of Fingrid directly. The problematic backup feeding situations are faults and maintenance which take place on 110 kV power lines. Furthermore, more than one substation has been connected to the same power line. This kind of power lines are power lines which are fed from Vihanti and Nivala (Figure 4.2).

For example, if a fault or maintenance is between Vihanti and Lumimetsä, it causes outgates for several substations. The power line feeds Haapavesi and Pulkkila directly and Piippola and Rantsila through Pulkkila. During the peak load, power could be over 30 MW. Part of 30 MW power will cover from 4 MW hydro power plant which is located between Pulkkila and Rantsila. Furthermore, there are a couple of connections to other network company from which about 2 MW power would be obtained. The rest of power should be obtained from Nivala through 45 kV network. However, this is not possible since the nominal power of the feeding transformer is 15 MVA. The changing of the transformer does not help a situation because it is not possible to transfer the needed power thermally with the present 45 kV power line and voltage drop would be a problem already on smaller power.

In order to the substations, which are connected to the power line of Vihanti, could be fed in the worst case of failure, 110 kV power line should be built from Nivala to Haapavesi. The length of the power line would be about 30 km and the estimated costs about 4 200 000 euro. [17]

During the peak load, it will be also difficult to backup feed substations which are fed from Nivala when the feeder of Nivala is out of service or a fault takes place between Nivala and Vasaratie. In that case, the substations of Haapajärvi, Hitura and Vasaratie should be fed from Vuolijoki. However, the power of the substations which are fed from Vuolijoki can be total over 70 MVA in the winter, in which case, voltage drop would be excessive on the substations of Hitura and Vasaratie. Voltage would be about 99 kV on both substations which is under an allowed voltage in the backup feeding situations ($0{,}90{*}U_n$). Thus, Vuolijoki – Ruotanen power line should be reconstructed in order to the backup feeding succeed on the peak loads of the winter and considering possible load growth.

4.3. Central Finland

In Central Finland, there are 215 km of 110 kV regional network and 29 substations from which four are 45/20 kV substation. Most of the substations are directly connected to the main grid or they are located at the end of 110 kV power lines of VFV. Koivisto – Pihtipudas and Keljo – Muurame are the only power lines where located more than one substation.

Koivisto – Pihtipudas power line also continues from Pihtipudas to Nivala and Vuolijoki so that disconnector is open the north side of Pihtipudas. Keljo – Muurame power line also continues a few kilometers from the substation of Muurame to Mäntylä which is customer’s substation. The regional network of Central Finland is introduced in Figure 4.4.

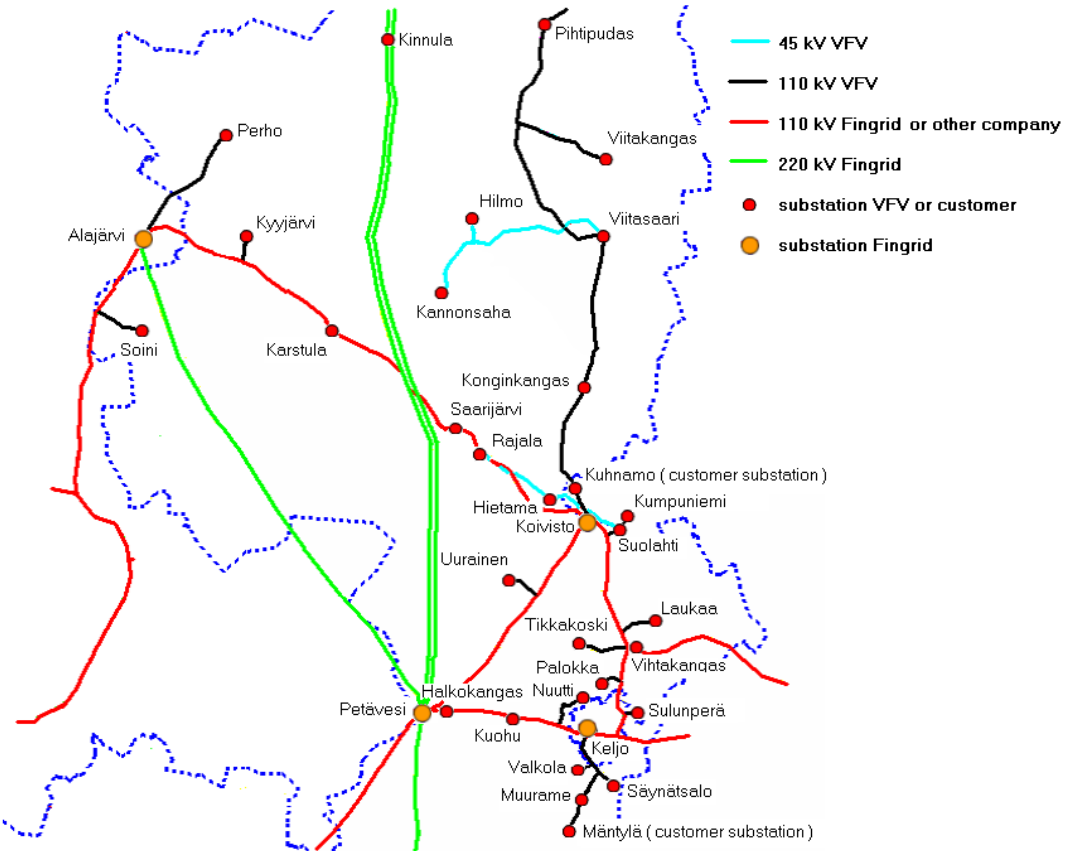


Figure 4.4 *Regional network of Central Finland.*

The power lines of VFV are illustrated with black and light blue lines. The 110 kV power lines of Fingrid or other company are illustrated with red lines. Furthermore, the 220 kV power lines of Fingrid are shown with green lines. The regional network of other company is power line which leaves to the southwest from the substation of Alajärvi. In more detail, the substation of Soini has been connected to the power line of other company.

4.3.1. Age distribution and mechanical condition of power lines

The oldest 110 kV power lines of Central Finland were built in the 1970's. The oldest is Koivisto – Viitasaari power line. The power line was built in 1973 and its length is 55 km. The mechanical condition of the power line is also the most weak of the power lines of the area. Weathering has been perceived with 25 % of the foundations and rotting with 20 % of the poles. Thus, the power line should be reconstructed as the first one of the power lines of Central Finland.

In addition, Keljo – Säynätsalo is power line which was built in 1970's and its mechanical condition is weak. The length of the power line is 11 km and weathering has been perceived with 15 % of the foundations and rotting with 10 % of the poles. Keljo – Säynätsalo power line should be also reconstructed from the power line of However, it can be assumed that the lifetime of the power line is still left 10...15 years.

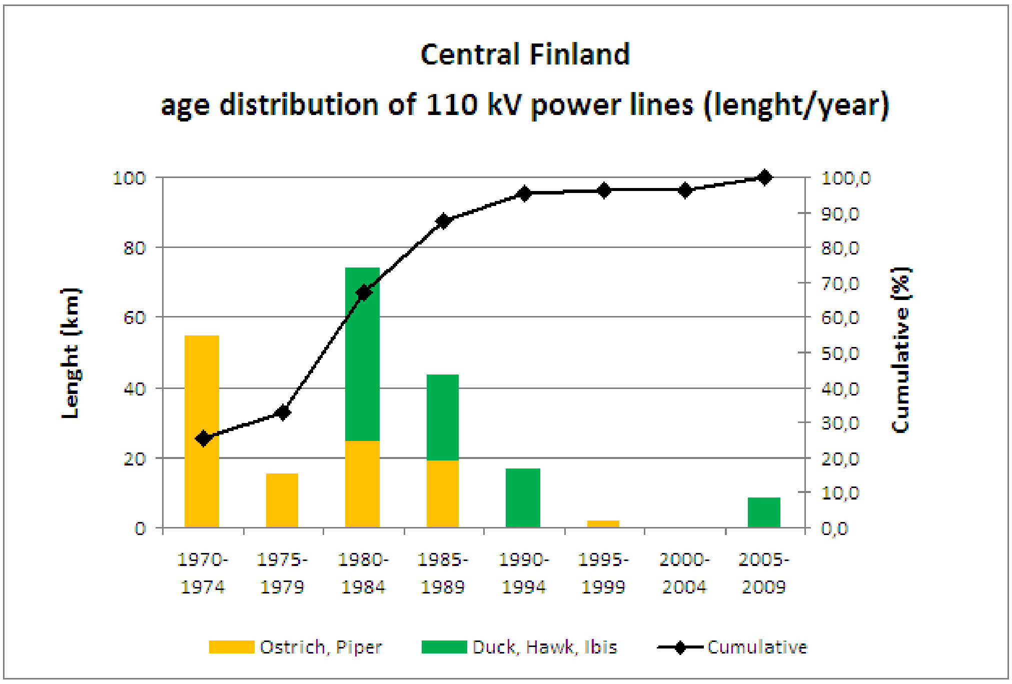


Figure 4.5 *Age distribution of 110 kV power lines according to the conductors.*

Figure 4.5 shows the age distribution of 110 kV power lines. A third of the power lines were built in 1970's. This amount consists of the above mentioned Koivisto – Viitasaari and Keljo – Säynätsalo power lines. As one can see from the figure, the majority of the power lines have been built in the 1980's. This means that there will be still lifetime left for several years on the most of power lines on the basis on the year of construction. The power lines are also mechanically in good order. Most observations in the inspections have been the loosening of stay wires which can be tightened in the following inspections.

4.3.2. Loading of main transformers

In Central Finland, all the substations are the substations of one main transformer. The nominal powers of the transformers are 471 MVA in total and the oldest transformers have been manufactured in the 1970's. All in all, eight transformers have been manufactured in the 1970's. Five of these have been serviced in 1996-2001.

The measured and calculated powers of the main transformers of Central Finland are presented in Appendix 2. Kumpuniemi, Tikkakoski and Sulunperä main transformers are in the load of more than 75 %. The main transformer of Tikkakoski is in the biggest load (84 %). The transformer will be changed for a bigger one 20 MVA transformer in the year 2011. However, the changing of the main transformer only improves the normal situation. The backup feeding of the substation is still difficult in the fault situation. Consequently, a light substation has been planned to connect the power line of Fingrid between the substations of Uurainen and Koivisto (Figure 4.1). The light substation would be improved the backup feeding of Tikkakoski and some of the present loads could be transferred for the new substation.

4.3.3. Backup feeding of substations

At the moment, the worst backup feeding situation is Keljo – Muurame power line in Central Finland. During the peak load, if a fault takes place between Keljo and Valkola, the three substations of VFV and the customer's one substation are without the electricity. The substations have to be fed through the medium voltage network.

However, the backup feeding of the substations is difficult through the medium voltage network. The substations of Halkokangas, Kerkkola, Kuohu, Kähö and Nuutti and two backup connections from Jyväskylän Energia have to be used in the backup feeding situation. Furthermore, there are about 2,5 MW of reserve power and 3,6 MVAr capacitor in use on the substation of Muurame. 2,4 MVAr capacitor is also use in the centre of Korpilahti. Despite backup connections, voltage drop is about 11 % on the feeders which are fed from the substations of Kähö and Nuutti. This means that the backup feeding does not succeed within allowed limits with present backup connections and in the worst fault situation.

Consequently, 110 kV backup connection has been planned from the substation of Toivila to Mäntylä. The length of the new power line would be about 36 km. The preliminary line of the power line is shown on a black dash line in Figure 4.6.

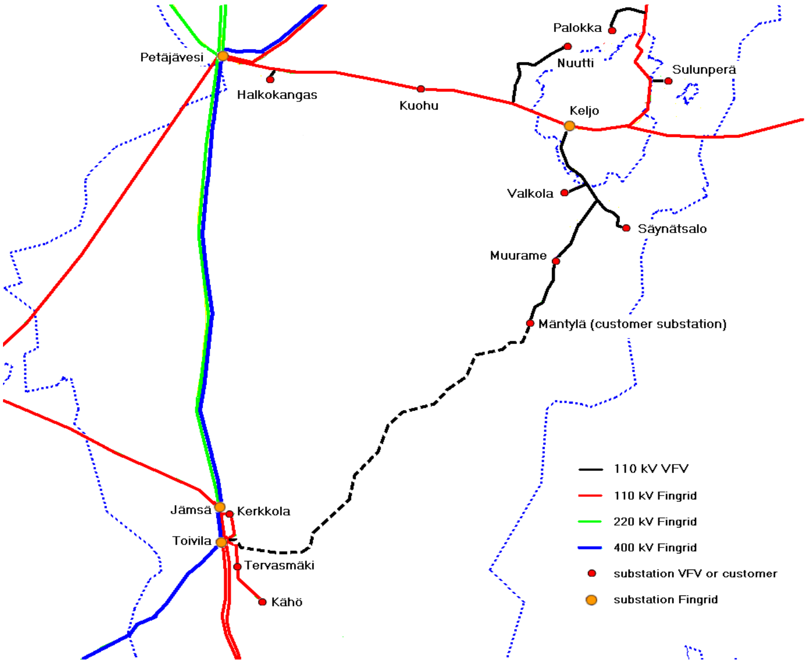


Figure 4.6 *Toivila – Mäntylä backup connection.*

The building costs of the power line would be about 5 830 000 euro including the connection to the substation of Toivila and the building of the additional bay to the substation of Mäntylä [15]. The building of Toivila – Mäntylä power line improves the delivery reliability of substations essentially. Furthermore, it would be possible to connect new substations to the power line if the loads of Jämsä area increase in the future.

The weak backup feeding situation is also on Koivisto – Pihtipudas substations. The backup feeding from Vuolijoki to Kuhnamo will succeed for seven months (April – October) in year in which case the power of substations, which is fed from Vuolijoki, is no more than 50 MW in total. In that case, voltage will vary 103…107 kV in Kuhnamo depending on what is the voltage on the substation of Vuolijoki (118…121 kV).

During the peak load, the power of substations can be about 70 MW. In that case, voltage is less than 100 kV in Konginkangas and Kuhnamo. Thus, Vuolijoki – Ruotanen power line should be reconstructed in order to the backup feeding would succeed at least to Konginkangas also on the peak loads.

4.4. Häme and Pirkanmaa

In Häme and Pirkanmaa, there are about 480 km of 110 kV power lines in total which is nearly half of all 110 kV power lines of VFV. There are also 59 the 110/20 kV substations, which nominal power is about 1380 MVA in total.

More than one substation are connected to the power lines of Nokia and Hämeenlinna, Tikinmaa – Forssa and Tikinmaa – Luopioinen power lines, Vanaja – Kuhmoinen power line and Heinola – Hartola power line. Other substations are located at the end of a radial power line owned by VFV or they have been directly connected to the main grid or the power line of other company.

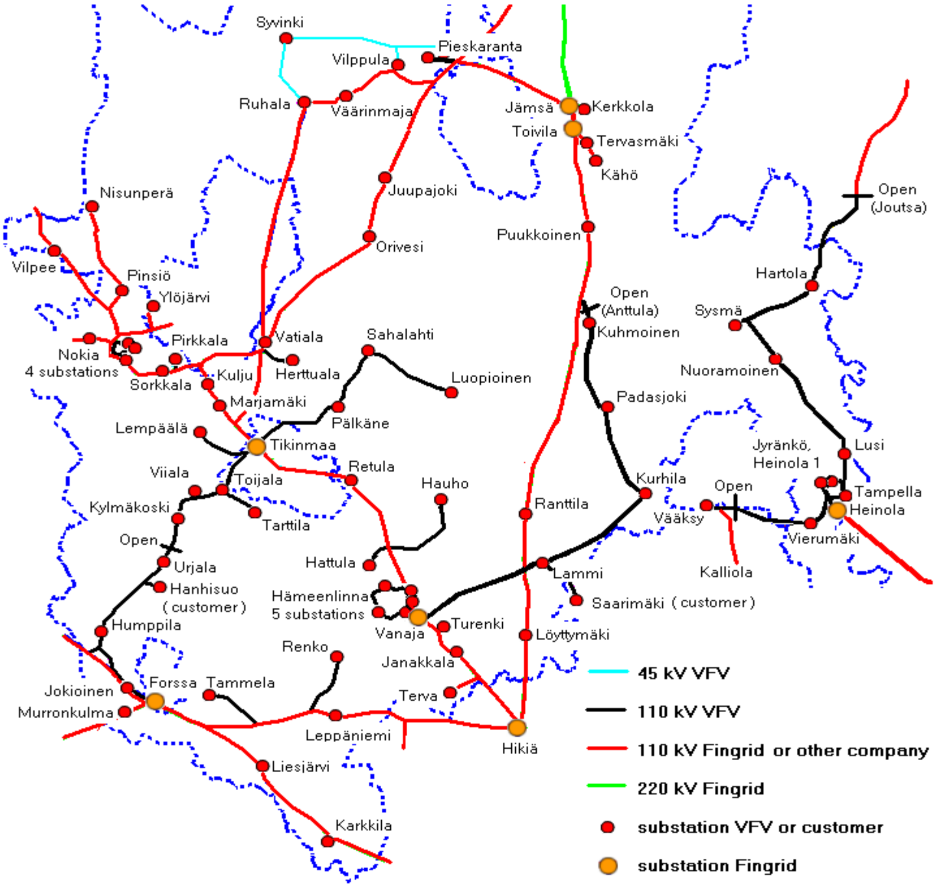


Figure 4.6 *Regional networks of Häme and Pirkanmaa.*

Figure 4.6 shows the regional networks of Häme and Pirkanmaa. The longest power line is about 110 km long Vanaja – Anttula power line. Five substations of VFV and one customer's substation have been connected to the power line.

Most substations are located on Tikinmaa – Forssa power line. There are eight substations of VFV and two customer's substations. The loads of Tikinmaa – Forssa power line have been divided so that the disconnector is open between Kylmäkoski and Urjala. In the normal situation, the power which is fed from Tikinmaa is maximum 60 MW and the power which is fed from Forssa is maximum 45 MW.

4.4.1. Age distribution and mechanical condition of power lines

About 55 % of the power lines of Häme and Pirkanmaa were built in the 1960's and the 1970's. The oldest Tampella – Nuoramoinen power line has been built in the year 1965 and it is 33 km long. Tikinmaa – Toijala power line and power line which feeds Herttuala have also been built at the end of 1960's. (Figure 4.6)

In spite of the age, Tampella – Nuoramoinen, Tikinmaa – Toijala and Herttuala power lines are still in good order. However, they should be reconstructed during the next fifteen years.

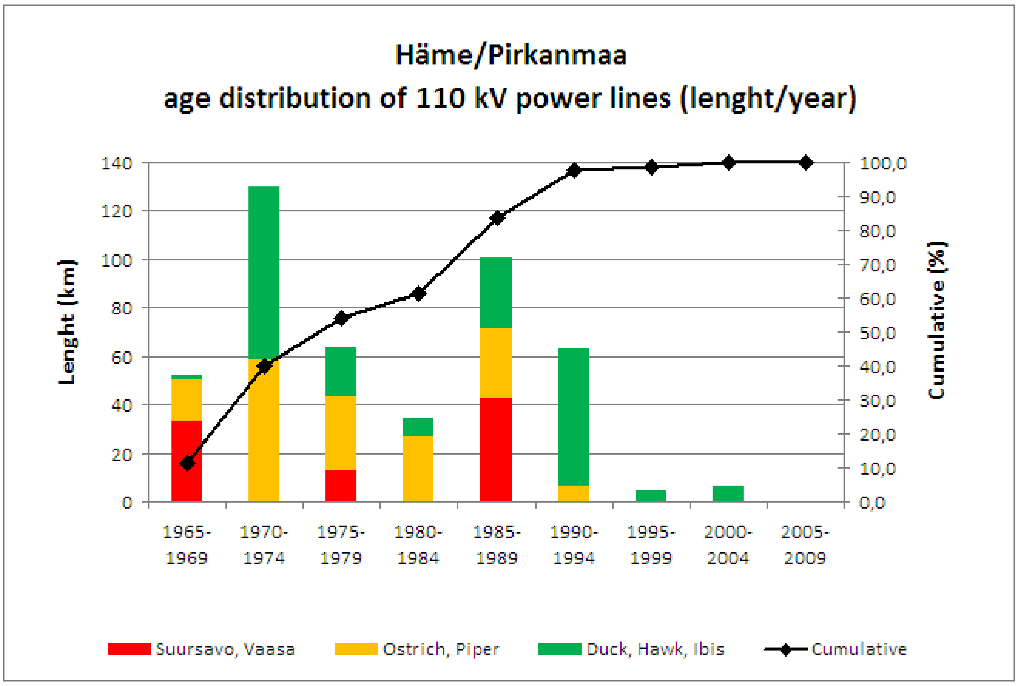


Figure 4.7 Age distribution of 110 kV power lines according to the conductors.

Figure 4.7 shows the age distribution of 110 kV power lines in Häme and Pirkanmaa. As one can notice from the figure, the regional network was built most in the early 1970's. The regional network was built about 130 km at that time. All in all, about 200 km of the regional network has been built in the 1970's which is 41 % of the 110 kV network of Häme and Pirkanmaa.

The weakest power line that has been built in 1970’s is about 20 km long Urjala – Humppila power line. On the basis of the inspection information of the years 2006 and 2008, weathering has been perceived with 20 % of the foundations and rotting with 28 % of the poles. Other power lines that have been built in the 1970's and after that are still in good order so there will be a lifetime left for several years.

4.4.2. Loading of main transformers

The measured and calculated powers of the main transformers are introduced in Appendix 3. The main transformers, which are in over 50 % loads or the main transformer has been manufactured in 1960’s, have been listed to the table. Harjuniitty, Lempäälä, Luolaja and Tervasuo are in the biggest load (>75 %). Harjuniitty and Tervasuo are located in Nokia and Luolaja is located in Hämeenlinna.

The loading of above mentioned substations can be lightened in three ways; by changing a bigger main transformer, by adding a second main transformer or by building a light substation. The loading of Lempäälä could be lightened by changing the current main transformer for a bigger one. Due to the rated current of 20 kV switchgears, the main transformers of Harjuniitty, Luolaja and Tervasuo can not be changed for bigger ones. For this reason, second main transformer will be added to Luolaja during the year 2011. The lightening of Harjuniitty and Tervasuo requires the changing of the medium voltage network topology in Nokia.

4.4.3. Backup feeding of substations

Tikinmaa – Luopioinen power line will be the most difficult to backup feed if a fault take place between Tikinmaa and Pälkäne. The substations of Pälkäne, Sahalahti and Luopioinen are located on the power line. Furhermore, the substation of Valkeakosken Energia has been connected to the power line. When the feeder of Tikinmaa is out of service or a fault take place between Tikinmaa and Pälkäne, all the four substations will be without the electricity.

During the peak load, the backup feeding of the substations is difficult since the distances between the substations are long and the power needed by the substations can be 30 MW in total. Especially, the backup feeding of Sahalahti is difficult for the reason that the needed power can be about 15 MW. Sahalahti is fed from Herttuala and Orivesi. However, the problem is that the voltage drop would be over 10 % when the feeders of Sahalahti are fed from Herttuala.

Due to the backup feeding situation of the substations, the 110 kV backup connection has been planned to build from Hikiä – Jämsä power line to Luopioinen. The length of 110 kV power line would be about 22 km. The costs of the backup connection would be about 3 550 000 euro including connections to the substation of Luopioinen and the branch of Auttoinen [15]. The backup connection is shown on a black dash line in Figure 4.8.

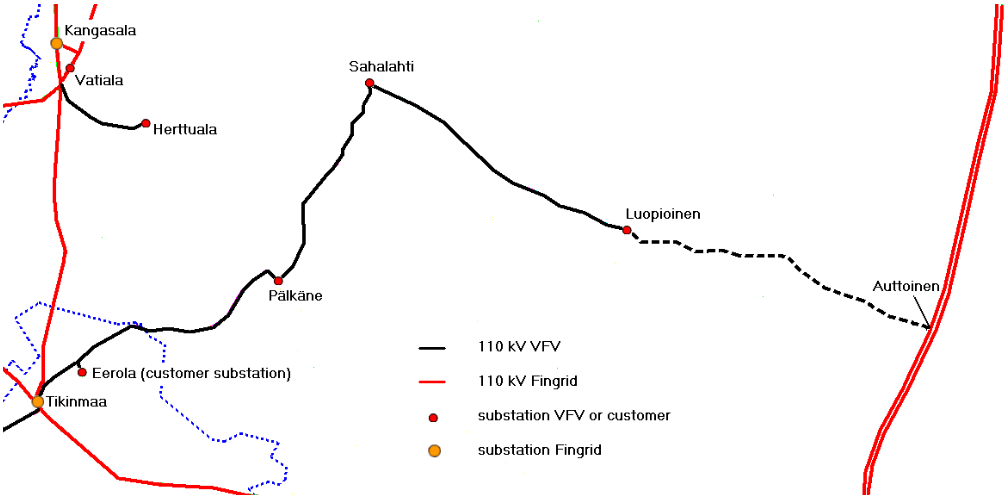


Figure 4.8 *Luopioinen – Auttoinen backup connection.*

In Häme and Pirkanmaa, the backup feedings of the other 110 kV power lines succeed with the present connections. For example, Tikinmaa – Forssa power line is possible to feed to both directions if the feeder is out of service in Tikimaa or Forssa. Furthermore, the substations of Vanaja – Kuhmoinen power line are possible to feed from the Hikiä – Jämsä power line if the feeder of Vanaja is out of service or between Vanaja and Lammi is a fault.

The substations of Heinola area could be fed from Kalliola and Joutsa if the substation of Fingrid is out of service. In the backup feeding situation, it would be fed from Joutsa to Lusi and from Kalliola to the centre of Heinola. (Figure 4.6)

5. FACTORS AFFECTING REGIONAL NETWORK

5.1. Northern Ostrobothnia

In the Northern Ostrobothnia, load growth, wind power and the development plan of the main grid have been examined as factors which possibly affect the development of the regional network.

5.1.1. Load growth

The loads of substations are predicted to increase by about 2 % per year until 2025. The effect of load growth has been examined for the load capacity and voltage drop of 110 kV power lines in normal situation and backup feeding situation. The over loads of the main transformers are not take into consideration since the loading are monitored monthly.

In the normal situation, there will be no problems with the load capacity and voltage drop of power lines. In the 2025, the biggest load would be on Nivala – Vasaratie power line which would be about 60 % of the maximum load capacity (Appendix 4).

Instead, the problems that have been presented in Chapter 4.2.3 (Backup feeding of substations) would increase in the backup feeding situation when the loads increase according to the prediction. The power of the substations, which are fed from Vihanti, would be about 45 MW during the peak load. At this moment, it would be possible to feed about 20 MW with the existing backup connection. Thus, 110 kV backup connection should be in use in order to the backup feeding would be succeed in the worst case.

Also the backup feeding from Vuolijoki to Vasaratie would become more difficult in the year 2025. Table 5.1 shows the loads and voltages of the substations which are fed from Vuolijoki during the peak load. It has been assumed that the voltage is 118 kV on the substation of Vuolijoki.

Table 5.1 *Power and voltages of substations.*

Substation	Power 2025 (MW)	Voltage (kV)
Pyhäsalmi	11,0	101,5
Pyhäjärvi	13,8	100,7
Haapajärvi	34,3	97,9
Hitura	6,1	96,5
Vasaratie	15,4	96,3

As from the table is seen, the voltage of substations would be less than 100 kV in Haapajärvi, Hitura and Vasaratie. Even though, the lowest allowed voltage is 100 kV in the backup feeding situation, the minimum voltage would be good to be 105 kV. For this reason, the rapid voltage change could be 15 kV when it is transferred from normal situation to backup feeding situation. The rapid voltage change is already affecting 20 kV voltage due to the on-load tap changer of the main transformer does not have time to act quickly enough.

5.1.2. Wind power

At the moment, wind power is one of the most important renewable energy sources. The growth of the wind power production has been very rapid over the past decade. The wind power capacity of the world has increased from the year 2001 for the year 2009 an average 23 % per year being 159 213 MW at the end of the year 2009. [18]

In Finland, growth has not been as fast as in the world. During the ten last years, the growth has been 18 % per year on an average. The wind power capacity was 197 MW in March 2010. [19]

Ministry of Employment and the Economy (EEM) has set as the goal in a long-term climate and energy strategy that wind power capacity would be 2500 MW in the 2020 [20]. This means that a new wind power capacity should be installed about 230 MW every year in order to the goal will be achieved. To reach goal, it has been set a support system for the wind power in which case the producer gets a guaranteed price from the produced energy. The guaranteed price is 83,5 euro per MWh and it will be valid during 12 years. Furthermore to the ones who invest fast, an additional bonus has been given until the year 2015 when the guaranteed price is 105,3 euro per MWh. Wind power plants are admitted to the support system until the total power of generators exceed 2500 MW. Teemu Kontkanen has presented in his master's thesis that technical and economic viable wind power capacity is 3275 MW in Northern Ostrobothnia. [21; 22]

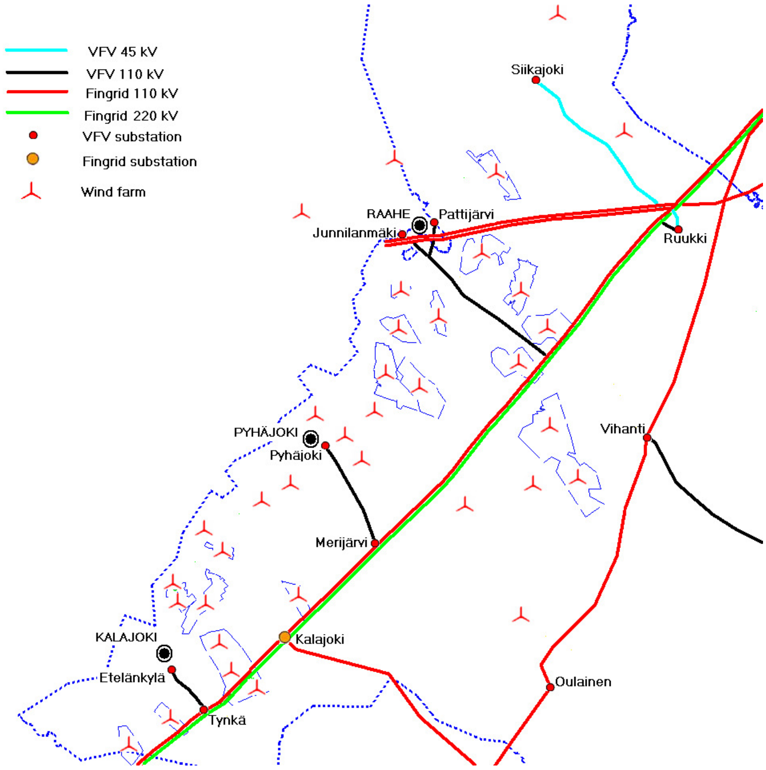


Figure 5.1 *Wind power projects of Northern Ostrobothnia.*

Figure 5.1 shows the wind power projects of Northern Ostrobothnia which VFV has known by March 2011. Furthermore, the regional network of VFV and power lines of Fingrid are shown in the year 2010. The power of the wind farms varies between 15…250 MW. The total power of wind farms is 2625 MW which is more than MEE has set as the target to build in a distributed in the Finland by the year 2020. Furthermore, the power is more which is admitted to the support system. Thus, it will be very probable that all planned wind power capacity does not realize to the area. By March 2011, about 760 MW of wind power has been planned to the Kalajoki area, 535 MW to the Pyhäjoki area and 1330 MW to the Raahe area.

5.1.3. Development plan of the main grid

Fingrid reconstructs the main grid so that it will be possible to connect new power production to the network which is in accordance with the Finnish climate and energy strategy by the year 2020. Fingrid is ready to connect one new nuclear power plant and 2500 MW wind power to the main grid. [23]

Fingrid must reconstruct the network of the whole Ostrobothnia so that it will be adequate considering power production that has been planned to the area. The purpose of Fingrid is to replace the ageing 220 kV network of the area by the year 2020 by extending 400 kV network and developing 110 kV network. A significant part of the power lines of Ostrobothnia has been earlier constructed with 400 kV structure. The main grid of Northern Ostrobothnia is introduced in Figure 5.1.

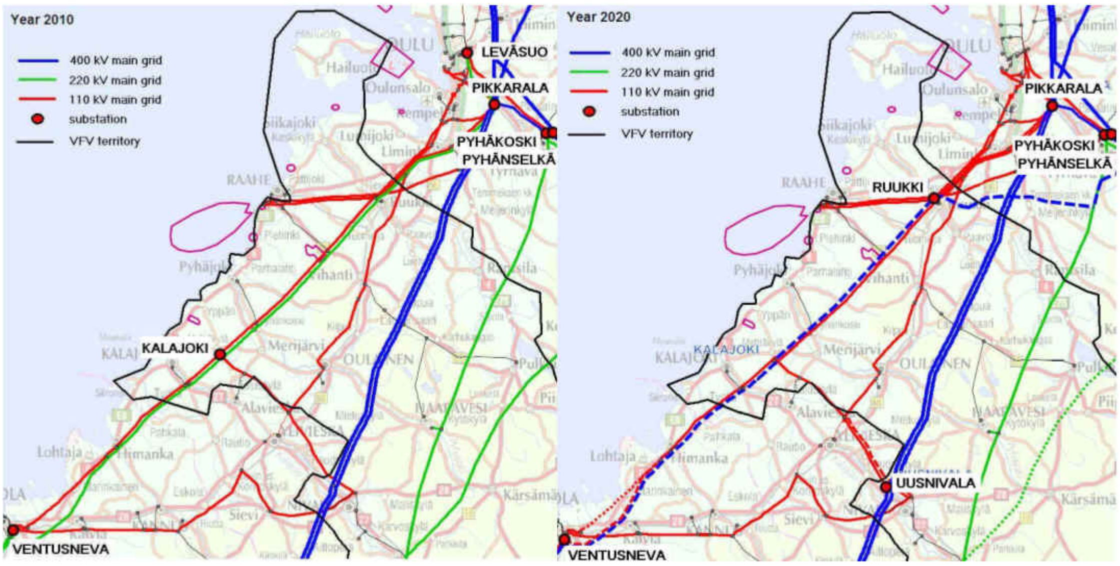


Figure 5.1 *Development plan of the main grid until 2020. The current network on the left and the 2020 network on the right.*

The current network is shown on the left and the 2020 network on the right. The backbone of the existing network is 220 kV substations; Ventusneva, Kalajoki, Leväsuo and Pyhänkoski together with 400 kV substations; Pikkarala and Pyhäselkä.

As a first of the network investments, Fingrid is building 400/110 kV substation to Uusnivala. The project is scheduled for completion in 2011. Uusnivala makes the building of new connections possible for VFV.

After 2015, Fingrid phases out the 220 kV voltage level of the west coast and builds 400 kV power line partly to the place of 220 kV power line. Furthermore, the necessary reconstructions are made for 110 kV power lines and possibly 400/110 kV substation will be built to Ruukki. If the wind farms are built several, other 400/110 kV substation will be connected to the 400 kV power line between Ruukki and Kalajoki. The most probable place is Kalajoki where the existing 220/110 kV substation is located currently. [23]

5.2. Central Finland

In the Central Finland, load growth and the development plan of the main grid have been examined as factors which possibly affect the development of the regional network.

5.2.1. Load growth

In Central Finland, it has been predicted that the loads of substations will increase 2 % per year on average until the year 2025. If the loads increase according to the prediction, it will affect Koivisto – Pihpudas power line also in normal situation. The voltage drop between Koivisto and Pihtipudas is about 10 kV. The voltage will be about 105 kV on the substation of Pihtipudas if the voltage is 115 kV on the substation of Koivisto. This is near the voltage drop which has been allowed in a normal situation ($0{,}95 \cdot U_n$). Because of this, the Koivisto – Viitasaari power line should be reconstructed if the loads increase according to the prediction.

The backup feeding situation of Koivisto – Pihtipudas substations will also worsen if the loads increase. During the peak load, the backup feeding will succeed only to Viitakangas in the year 2025. The power lines which leave Vuolijoki should be reconstructed in order to the backup feeding succeed at least to Konginkangas, In Chapter 7.1, Vuolijoki – Nivala – Koivisto regional network is examined in more detail considering load growth and the development plan of the main grid in Central Finland and Northern Ostrobothnia.

5.2.2. Development plan of the main grid

In Central Finland, the most significant change of the main grid is 220 kV power lines are brought into 110 kV use. The 220 kV power lines which are brought into 110 kV use are Petäjävesi – Jämsä and Petäjävesi – Alajärvi power lines (Figure. Furthermore, 400 kV power line will be built to the place of Petäjävesi – Pyhänselkä or Petäjävesi – Nuojua 220 kV power line and one power line will be brought into 110 kV use. The development plan of the main grid is introduced in Figure 5.3 until the year 2025. [25]

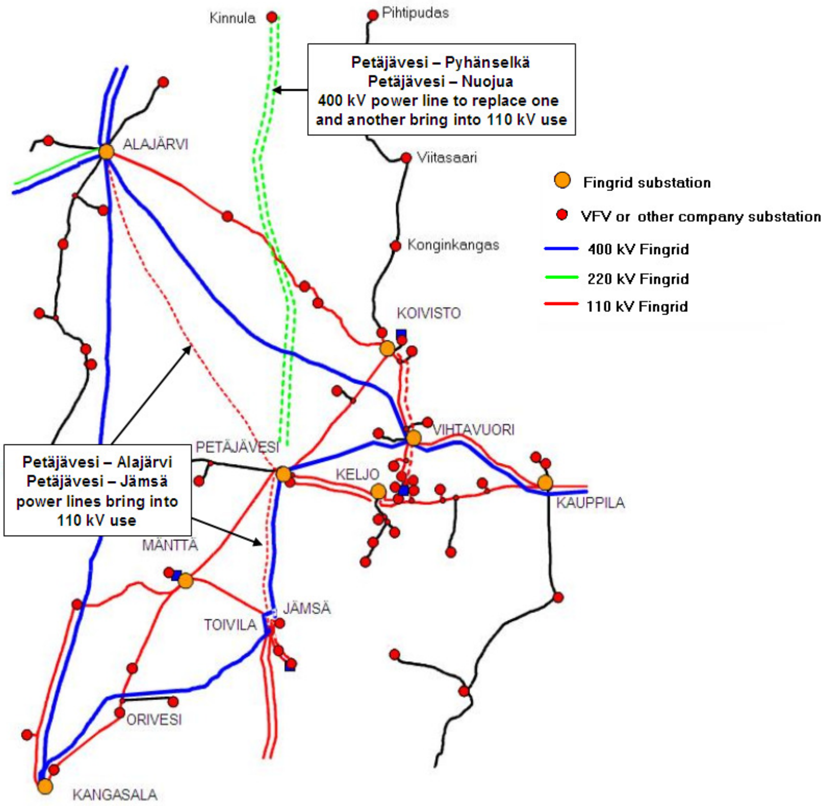


Figure 5.3 *Development plan of the main grid until the year 2025. [25]*

Existing Petäjävesi – Jämsä and Petäjävesi - Alajärvi 220 kV power lines, which are brought into 110 kV use, are illustrated on a red dash line. Petäjävesi – Pyhänselkä and Petäjävesi – Nuojua power lines are shown on a green dash line.

The new 110 kV power lines will bring opportunities to build new substations and connections for VFV. For example, the substation of Soini could be connected to Petäjävesi – Alajärvi power line whereby the delivery reliability of the substation improves. The length of the new power line would be about 5 km and its costs would be about 740 000 euro including the connection to the power line of Fingrid by line disconnector. [14]

After the change of voltage level, it would be possible to connect 110/20 kV light substation to Petäjävesi – Jämsä power line. The light substation could be used to improve delivery reliability in Jämsä and Petäjävesi area. Correspondingly, it would be possible to connect light substations to Petäjävesi – Pyhäkoski or Petäjävesi – Nuojua power line which could be used to replace ageing 45 kV power lines. The substation of Kannonsaha could be replaced by light substation in Central Finland and the substation of Reisjärvi in Northern Ostrobothnia (Figure 4.2 and 4.4). [25]

5.3. Häme and Pirkanmaa

In the Häme and Pirkanmaa, load growth and the development plan of the main grid have been examined as factors which possibly affect the development of the regional network.

5.3.1. Load growth

In Häme and Pirkanmaa, it has been predicted that the loads of substations will increase 2 % per year until the year 2025. In the normal situation, load growth does not have an effect on the regional network. The lowest voltage would be about 112 kV on the substation of Kuhmoinen when it is assumed that the voltage is 118 kV in the connection points of the main grid. Correspondingly, the biggest loading would be on the power line which leaves Heinola to Hartola. The loading would be about 70 % of the maximum load capacity.

In the backup feeding situations, there will be problems if the loads increase according to the prediction. If Tikinmaa – Forssa power line is fed from Tikinmaa to Jokioinen with the 2025 loads, Tikinmaa – Toijala power line would be in about 118 % load (Appendix 4). Correspondingly, if Tikinmaa – Forssa power line is fed from Forssa to Tarttila, the about three kilometers long power line between the substations of Jokioinen and Humppila would be in an about 115 % load. Furthermore, Humppila – Urjala power line would be in a hundred per cent load and the voltage would be about 103 kV in Tarttila. Thus, the reconstruction needs of Tikinmaa – Forssa power line are examined in more detail in Chapter 7.3.

5.3.2. Development plan of the main grid

The main grid investments of Fingrid have minor effect on the regional network of VFV in Häme and Pirkanmaa. However, the backup feeding of Tikinmaa – Vanaja power line allows for looped network in Hämeenlinna. According to the plans of Fingrid, Tikinmaa – Vanaja power line would be reconstructed in the year 2018 at which time VFV could be built about 4 km power line to the same poles. The evaluated costs of the power line would be about 1 060 000 euro including the connection to Vanaja. [17; 25]

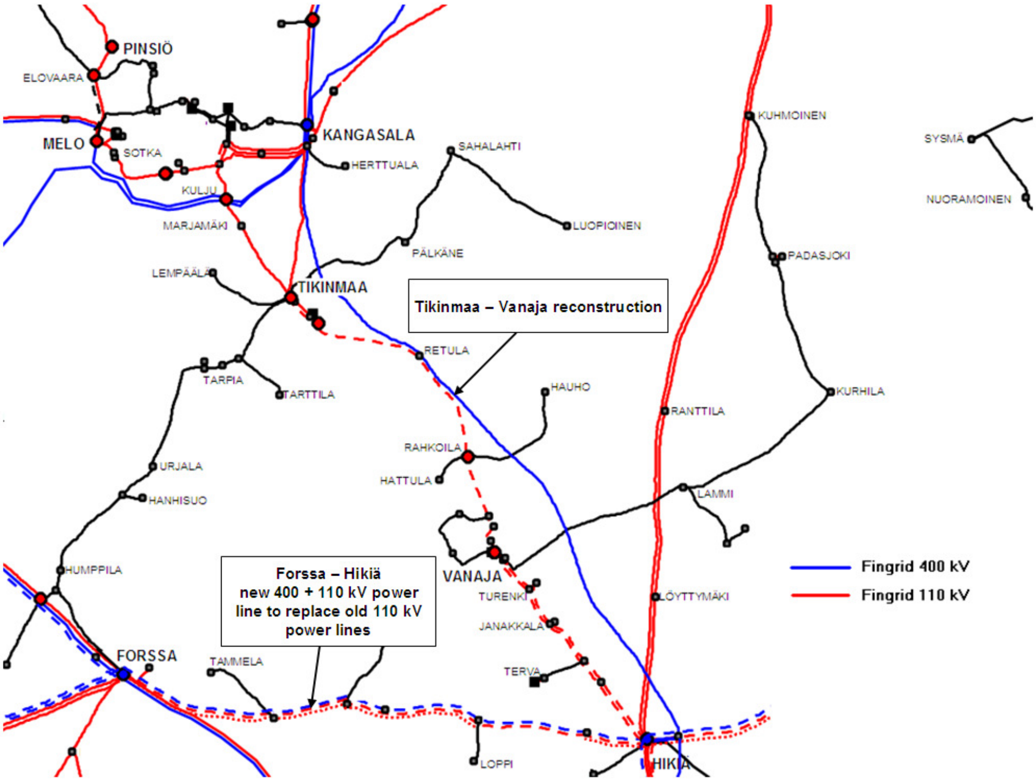


Figure 5.4 *Development plan of Häme and Pirkanmaa until 2025. [25]*

Development plan of Häme and Pirkanmaa are shown until 2025 in Figure 6.3. The 110 kV power lines, which Fingrid intends to reconstruct, have been presented on red dash lines and the new 400 kV power lines have been presented on blue dash lines. [25]

6. WIND POWER NETWORKS

6.1. General

The analysis of wind power networks has been divided into area of Kalajoki and Raahe. In the areas, wind power networks have been examined in three different scenarios. In scenarios, the estimated amounts of wind power capacity base on the numbers informed by wind power companies or areas which have been planned by provinces.

In all scenarios, it has been assumed that Fingrid has done the investments which where presented in Chapter 5.1.3 (Development plan of the main grid). Furthermore, the connection points of the main grid are in the 400/110 kV substations of Siikajoki and Kalajoki. Also, there is third connection point on 110 kV switchyard which is located near the center of Raahe.

6.2. Connection code for connection of wind power plants

In the connection code of the main grid, the power limits are classified for the wind farm when connecting to different voltage levels. When the nominal power of the wind farm is more than 250 MVA, it will be connected to 400 kV network. Correspondingly, 100 – 250 MVA wind farm could be connected to 110 kV or 400 kV network depending on the regional limitations. The smaller wind farms are usually connected to either directly 110 kV network or via 20 kV network. However, wind farms larger than 10 MVA connecting to regional networks also have to meet the following requirements. [24]

The active power of wind farm must be possible to control and the consumption and production of reactive power must remain within the limits. The upper limit of active power must be possible to set with accuracy of ± 5 %, in the range from 20 % to 100 % of the wind farm rated power. The upper limit of active power is measured as a 10 minute average value. The limit shall be adjustable by remote control. The ramping speed of active power is limited to 10 % of rated power per minute in upward control when increased production due to increased wind speed or due to changed maximum power output limit. There is no requirement to down ramping due to fast wind speed decays, but it must be possible to limit the down ramping speed to 10 % of rated power per minute, when the maximum power output limit is reduced by a control action. It must also be possible to regulate the active power from the wind power plant down from 100 % to 20 % of rated power in less than 5 seconds. This functionality is required for system protection. [24]

Fingrid gives individual settings for frequency control to the wind farms. The production of the active power is controlled proportionally to the frequency deviation of the system frequency and the control is automatic. In the frequency control, there must be deadband in which case the wind farm does not control active power according to the frequency.

The wind farm must have adequate reactive capacity to be able to be operated with zero reactive exchange with the network measured at the connection point when the voltage and the frequency are within normal operations limits. The reactive power must be controllable in one of the two following control modes: to keep the transfer of the reactive power to the network or from network inside certain limits determined by the Fingrid, in other words, as constant reactive power control, or control the voltage of the connection point with help of reactive power, in the other words, as constant voltage control. At the moment, constant reactive power control is used in the main grid of Finland. [26]

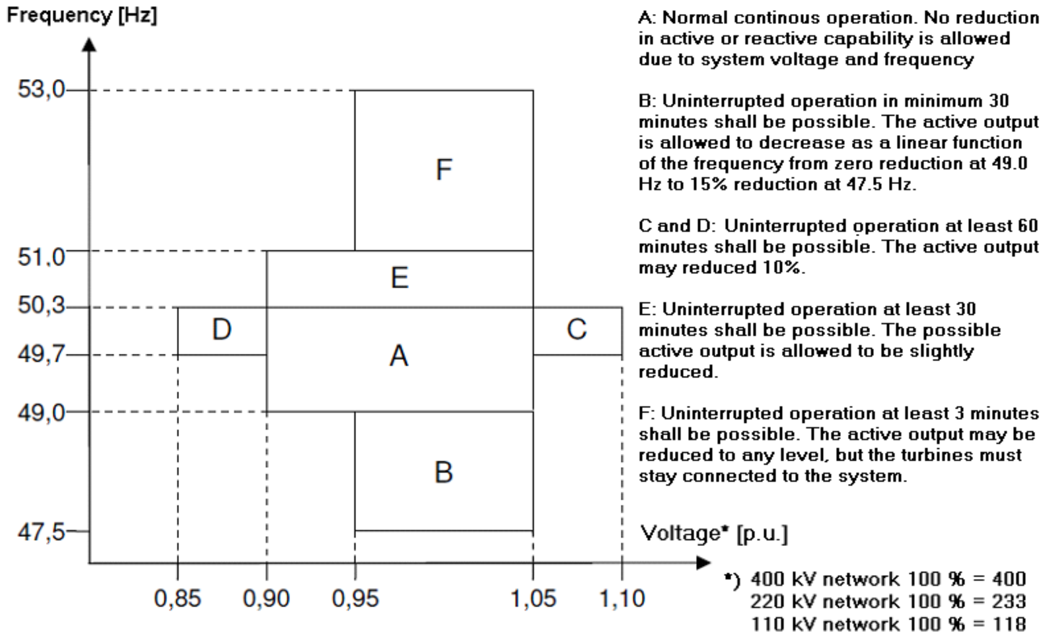


Figure 6.1 *Operating areas in regard to voltages and frequencies. [26]*

Figure 6.1 shows the operating areas of the network in regard to frequency and voltage. Normal continuous operation is in sector A. When the network frequency varies within the limits of sector B and F, uninterrupted operation shall be possible in minimum 30 minutes. If the voltage drops significantly, but the frequency remains normal, requiring at least 60 minutes uninterrupted operation according to sector D. When also the voltage increases over a normal upper limit but not more than 10 % of the nominal voltage and the frequency remains normal, the wind farm has to stay in the network at least 60min. In the situation of sector F, the active power may be reduced but the wind power plants must stay connected to network for at least 3 minutes.

In the disturbances of the main grid, a wind farm must be able to stay connected to the system and continue operation during and after dimensioning faults. A Wind farm may disconnect from the network if the voltage at the connection point do fall below the levels shown in the following Figure 6.2. [26]

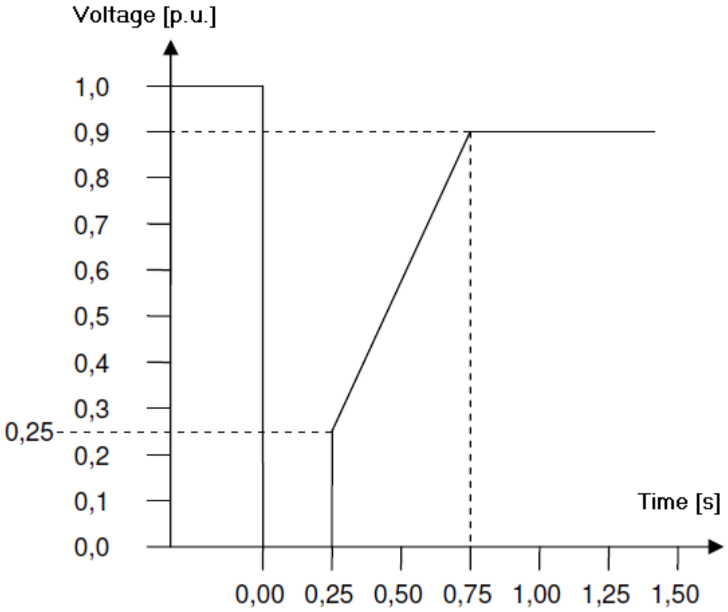


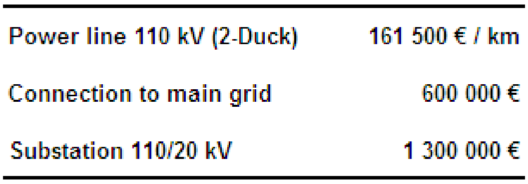
Figure 6.2 *Voltage dip, which the wind farm must tolerate without disconnecting from the network. [26]*

From Figure 6.2, it is seen that the wind farm has to stay in the network if the voltage returns within 0,25 seconds from at least 25 % of nominal voltage and the voltage increase to at least 90 % of the nominal voltage during the following 0,5s. Otherwise the wind farm may disconnect from the network and the synchronous use is lost.

6.3. Simulation of wind power networks

Wind power networks have been simulated with PSS/E program. In this thesis, it has only been used load flow calculation. The connection points of the wind farms have been selected on 110/20 kV substation in the network of VFV. Correspondingly, the connection points of the main grid have been selected on 110 kV busbar in 110 kV switchyard or 400/100 kV substation. Connection points have been selected on basis that VFV is responsible for the network components which are between the medium voltage network of wind power producers and the connection point of the main grid. Medium voltage network of wind farms and 400/110 kV substations have not been taken in account calculating costs of wind power networks. Hence, the connection to the main grid, 110 kV power lines and 110/20 kV substations have been taken into account calculating the costs. In the Table 6.1, costs are shown to above mentioned network components.

Table 6.1 *Costs of network components. [17]*



Power line 110 kV (2-Duck)	161 500 € / km
Connection to main grid	600 000 €
Substation 110/20 kV	1 300 000 €

Connection studies have been made so that voltage can be varying 116…120 kV at the connection point of the main grid. Furthermore, reactive power is zero at the connection point. This mean, that wind farms do not produce reactive power to the main grid and do not take reactive power from the main grid. The internal network of wind farms has been simulated by one generator and transformer so that nominal power of the generator has been set the total power of the wind farm. The nominal power of one transformer has been assumed 31,5 or 40 MVA depending on the maximum power of the wind farm.

6.4. Wind power projects of Kalajoki area

1100 MW of wind power projects have been planned to Kalajoki area by March 2011. In the first scenario, wind farms are estimated to realize 217 MW, in the second scenario 372 MW and in the third scenario 1100 MW.

6.4.1. Scenario 1 – Wind power capacity 217 MW

In the scenario 1, the estimated 217 MW of wind power capacity is based on the Environmental Impact Assessment (EIA) projects which have been on view in Centre for Economic Development, Transport and Environment of Northern Ostrobothnia (ELY-centre) during the years 2010 and 2011. In EIA, there have been Jokela, Mäkikangas and Tohkoja named wind farms in Kalajoki area. Wind power capacity 217 MW consists of the amount which has been reported as the alternative 1 in the EIA projects of the wind farms. [27]

In the alternative 1, Jokela wind farm has planned to build 14 wind power plants which total power is 50 MW. Correspondingly, Mäkikangas wind farm has planned to build 13 wind power plants which total power is 47 MW. Tohkoja wind farm has divided into two regions; Tohkoja A and B. In alternative 1, Tohkoja A wind farm has planned to build 30 wind power plants which total power is 90 MW. Tohkoja B wind farm has planned to build 10 wind power plants which total power is 30 MW. [28; 29; 30]

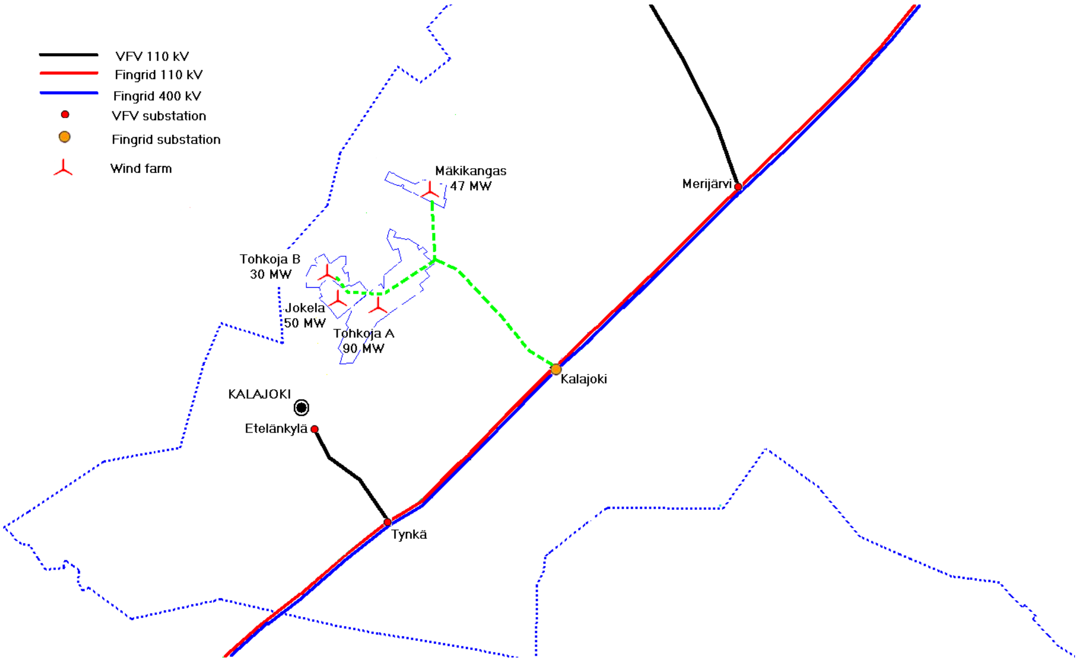


Figure 6.3 *Wind farms and wind power network of scenario 1.*

The wind farms and wind power network of scenario 1 are shown in Figure 6.3. All four wind farms could be connected to the substation of Kalajoki with 2-Duck conductor. The length of the power line is about 20 km. Wind farms should produce a total of about 30 MVAr reactive power during maximum power in order to the reactive power would be zero on the substation of Kalajoki. For this reason, voltage would be 122 kV at its highest on the substation of Tohkoja B when voltage is 120 kV on the substation of Kalajoki. The estimated costs of the wind power network are introduced in Table 6.2.

Table 6.2 *Costs of wind power network.*

Investment	Cost [M€]
Connection and 110 kV power lines	3.83
- connection to Kalajoki	
- 2-Duck, 20 km	
Substations (9 pcs)	11.70
- one substation including:	
- 110 kV bay	
- 31,5 or 40 MVA transformer	
- 20 kV switchgear	
Total	15.53

Wind power network consist of the connection to the substation of Kalajoki, about 20 km power line and nine substations if the nominal power of the transformer is 31,5 MVA. The total cost would be approximately 15,5 million.

6.4.2. Scenario 2 – Wind power capasity 372 MW

In scenario 2, wind farms are the same as in scenario 1, but the maximum power of wind farms is 372 MW in total. The total power is based on the amounts that have been reported as alternatives 2 in the EIA projects of the wind farms. The maximum powers of the wind farms would be Jokela 72 MW, Mäkikankas 68 MW, Tohkoja A 188 MW and Tohkoja B 45 MW. [28; 29; 30]

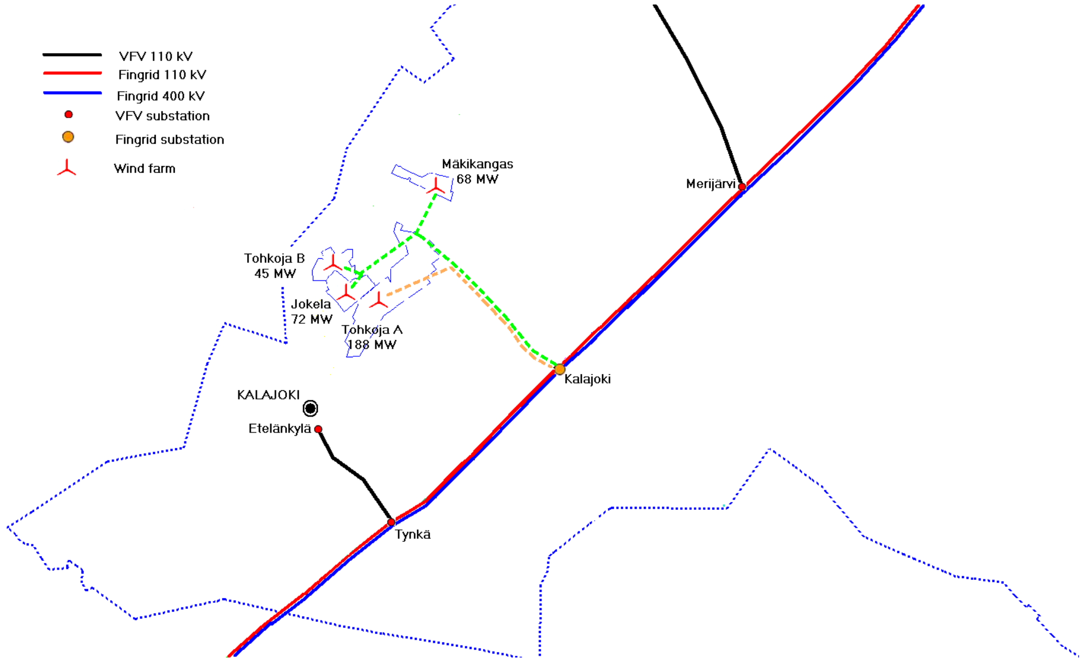


Figure 6.4 *Wind farms and wind power networks of scenario 2.*

The wind power networks are introduced in Figure 6.4 if wind farms would be built with maximum power. Depart from scenario 1, Tohkoja A should be connected to Kalajoki with own feeder and power line. The load capacity of 2-Duck conductor is about 260 MVA if the voltage is 118 kV and ambient temperature is 30℃ degrees. This mean that wind farms can not be connected to Kalajoki with one 2-Duck conductor. The estimated costs of wind power networks are shown in Table 6.3.

Table 6.3 *Costs of wind power network.*

Investment	**Cost [M€]**
Connections and 110 kV power lines	6.37
- two connections to Kalajoki	
- 2-Duck, 32 km	
Substations (12 pcs)	15.60
- one substation including:	
- 110 kV bay	
- 31,5 or 40 MVA transformer	
- 20 kV switchgear	
Total	21.97

About 12 km of the power line should be built more than in scenario 1. Furthermore, substations would need to build three more even if the nominal power of the transformers is 31,5 or 40 MVA.

Power lines are useful to build on the same poles if Jokela, Mäkikangas and Tohkoja wind farms are realized at the same time. In that case, the costs will lower because so broad the right-of-way does not need to be built.

6.4.3. Scenario 3 – Wind power capacity 1100 MW

In scenario 3, it has been examined wind power networks if all 1100 MW wind power capacity would be realized. The powers of wind farms are based on the numbers informed by the wind power companies or estimated numbers on the basis of the planned areas. The biggest individual wind farm would be Tohkoja A (188 MW) and the smallest Pyhäjoki X (15 MW). Pyhäjoki B includes two 125 MW wind farm. The wind farms and wind power network of scenario 3 are shown in Figure 6.5.

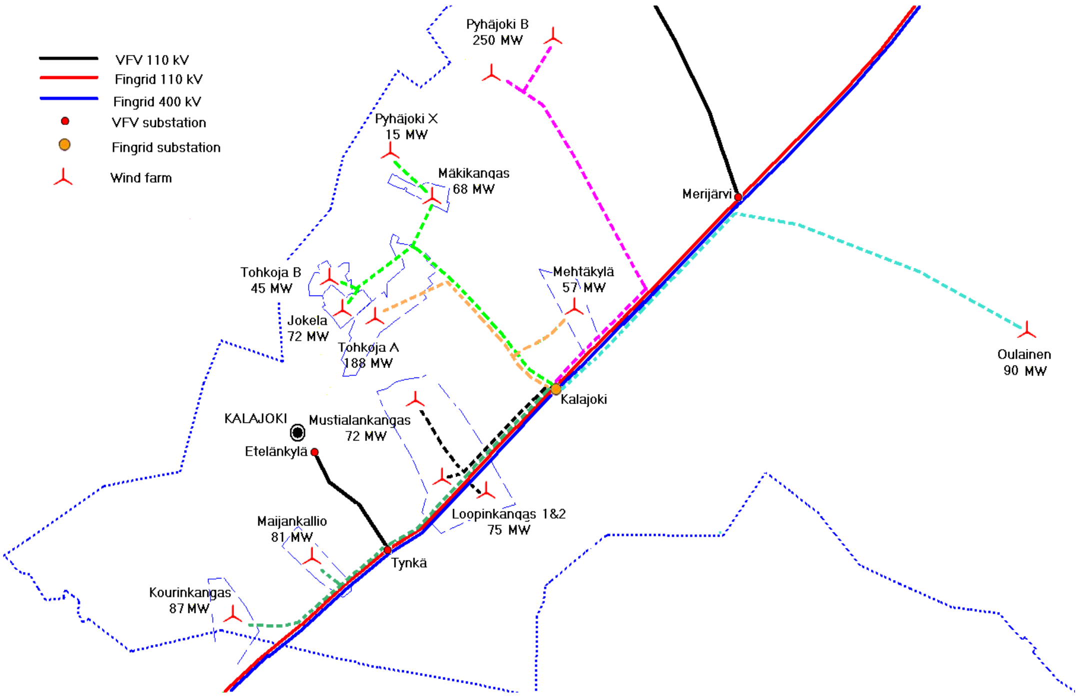


Figure 6.5 *Wind farms and wind power network of scenario 3.*

The power lines at different colors present own feeder from Kalajoki. Four feeders would be needed more than in scenario 2. Furthermore, Mehtäkylä wind farm could be connected to Tohkoja A power line and Pyhäjoki X wind farm to Mäkikangas – Tohkoja B power line. After this, about 50 MW more power would be able to connect to Mäkikangas – Tohkoja B power line.

The power line which feeds the wind farm of Oulainen would be the longest of the power lines. The estimated length of the power line would be about 30 km. About 200 MW is able to connect to the power line of Oulainen in maximum. The maximum operating voltage of 110 kV devices (123 kV) would become a restricting factor. If the wind farm produced more power than 200 MW, the voltage should be more than 123 kV on the substation of the wind farm when the voltage is 120 kV on the substation of Kalajoki. It would be possible to connect a maximum 250 MVA load on other power lines allowed by 2-Duck conductor. On the substations of wind farms, voltages would be below 123 kV although the voltage would be 120 kV in Kalajoki. Table 6.4 shows the estimated costs to the wind power networks of scenario 3.

Table 6.4 *Costs of wind power networks.*

Investment	Cost [M€]
Connections and 110 kV power lines	23.79
- six connections to Kalajoki	
- 2-Duck, 125 km	
Substations (32 pcs)	41.60
- one substation including:	
- 110 kV bay	
- 31,5 or 40 MVA transformer	
- 20 kV switchgear	
Total	65.39

Six connections would be needed to the substation of Kalajoki and power lines about 125 km. Furthermore, 32 substations should be built if the power of the main transformer is 31,5 or 40 MVA. The estimated total costs would be about 65 million euro including the substations of wind farms.

6.5. Wind power projects of Raahe area

1525 MW of wind power projects have been planned to Raahe area by March 2011. In the first scenario, wind farms are estimated to realize 514 MW, in the second scenario 1033 MW and in the third scenario 1525 MW.

6.5.1. Scenario 1 – Wind power capacity 514 MW

In the scenario 1, the estimated 514 MW of wind power capacity is based on the EIA projects which have been on view in ELY-centre of Northern Ostrobothnia during the year 2010-2011. Kopsa wind farm, the southern wind farms of Raahe and Siikajoki wind farm belong to the wind farm projects of Raahe area. [27]

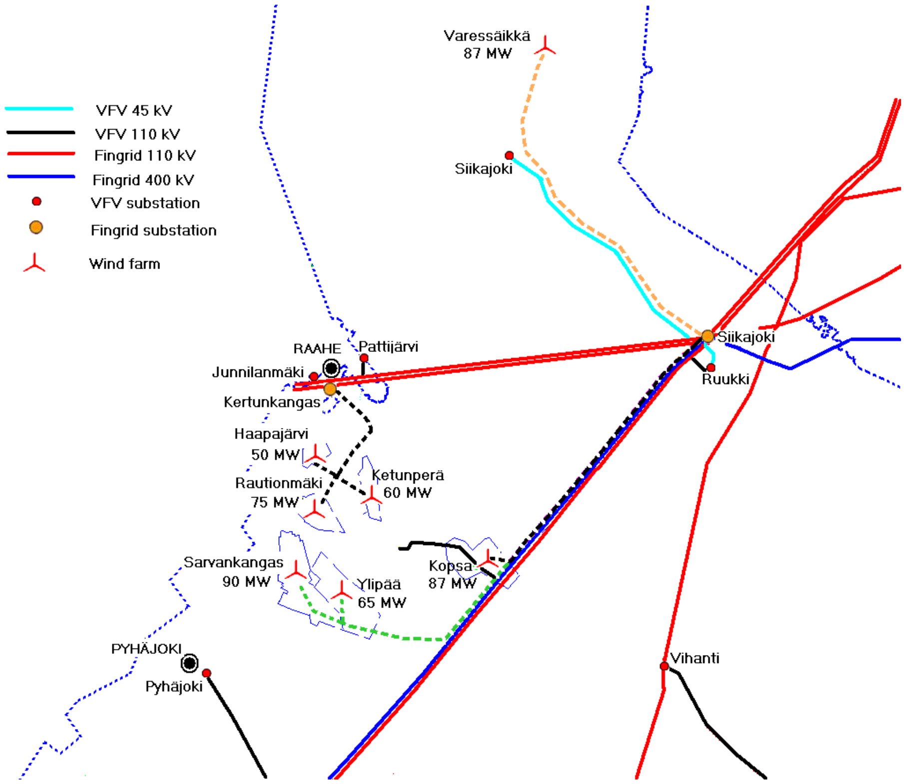


Figure 6.6 *Wind farms and wind power network of scenario 1.*

Wind power networks of scenario 1 are introduced in Figure 6.6. Haapajärvi, Ketunperä, Rautionmäki, Sarvankangas and Ylipää belong to the southern wind farms of Raahe projects and Varessäikkä belongs to Siikajoki wind farm project. [31;32]

Based on the information of Fingrid, it would be possible to build 110 kV switchyard to Junnilanmäki, Kertunkangas or Mustalampi near the center of Raahe. In this thesis, the switchyard is assumed to locate in Kertunkangas. It is possible to connect about 200 MW of a wind power to the switchyard. [33]

The estimated wind power capacities of Haapajärvi, Ketunperä and Rautionmäki are based on amounts which have been reported in EIA-projects. If wind farms are realized with maximum wind power capacities, they could be connected to the switchyard of Kertunkangas. After that, it could be possible to connect 15 MW power to Kertunkangas.

The wind power capacities of Sarvankangas and Ylipää have been estimated on the basis of which possible is connected with one 2-Duck conductor and 110 kV nominal voltage to Kalajoki. The estimated power is a total of about 155 MW. Voltage would be over 123 kV on the substation of wind farms if Sarvankangas and Ylipää produced more power than 155 MW and voltage is 120 kV in Siikajoki. The costs of wind power network are shown in Table 6.5.

Table 6.5 *Costs of wind power network.*

Investment	Cost [M€]
Connections and 110 kV power lines	22.66
- three connections to Siikajoki	
- 110 kV switchyard to Karhunkangas	
- 2-Duck, 118 km	
Substations (18 pcs)	23.40
- one substation including:	
- 110 kV field	
- 31,5 or 40 MVA transformer	
- 20 kV switchgear	
Total	46.06

Three connections would be needed to Siikajoki. Furthermore, it would be reasonable to build a switchyard to Karhunkangas. The switchyard of Karhunkangas has been calculated according to costs because it would be built in practice for wind farms. The costs of Karhunkangas consist of three 110 kV circuit-breaker bays, which costs would be about 1,8 million euro in total. The power lines should be built about a total of about 118 km. Furthermore, substations would be needed 18, if the power of transformer was 31,5 or 40 MVA.

6.5.2. Scenario 2 – Wind power capacity 1033 MW

In scenario 2, the eastern wind farms of Raahe have been examined in addition to the wind farms of the scenario 1. Annankangas, Nikkarinkaarto, Yhteinenkangas, Someronkangas and Hummastinvaara belong to the eastern wind farms of Raahe. The powers of wind farms are based on the numbers informed by the wind power companies. It has been estimated that the wind power capacity of the eastern wind farms is about 477 MW in total. The wind power networks of scenario 2 are shown in Figure 6.7.

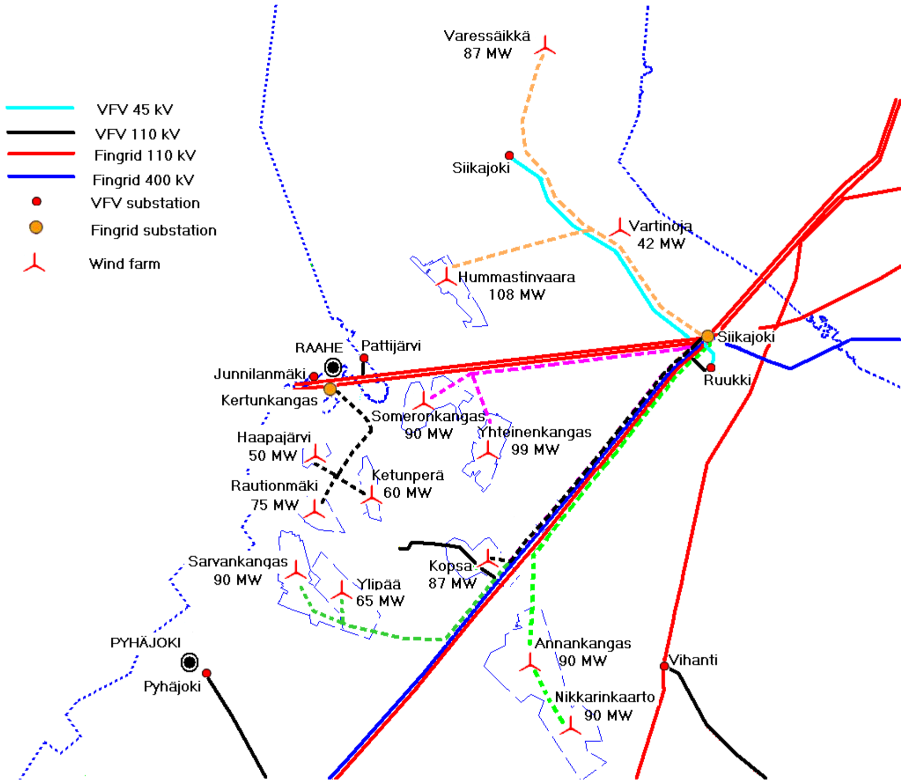


Figure 6.7 *Wind farms and wind power network of scenario 2.*

Annankangas and Nikkarinkaarto could be connected to the substation of Siikajoki with 2-Duck conductor. The length of the power line would be approximately about 35 km. The estimated 180 MW total power of the wind farms would also be maximum power which could be transferred to the substation of Siikajoki considering reactive power compensation and voltage increase on the substations of the wind farms.

Someronkangas and Yhteinenkangas should be connected to the substation of Siikajoki with own feeder and power line. It would be possible to connect about 50 MW adds wind power to the power line. Hummastinvaara and Vartinoja could be connected to the power line of Vareissäikkä. The length of Vartinoja – Hummastinvaara power line would be about 11 km. The costs of wind power networks are illustrated in Table 6.6.

Table 6.6 *Costs of wind power networks.*

Investment	Cost [M€]
Connections and 110 kV power lines	36.13
- five connections to Siikajoki	
- 110 kV switchyard to Karhunkangas	
- 2-Duck, 194 km	
Substations (34 pcs)	44.20
- one substation including:	
- 110 kV field	
- 31,5 or 40 MVA transformer	
- 20 kV switchgear	
Total	80.33

The connections to the substation of Siikajoki would be needed two more than in the scenario 1. Furthermore, about 90 km of the power lines should be built more. The substations would be needed 34 pieces. The total costs would be about 80 million euro.

6.5.3. Scenario 3 – Wind power capacity 1525 MW

In the scenario 3, it has been assumed that wind power capacity would be 1525 MW. If the amount in question came true, it would be reasonable to build third 400/110 kV substation between the substations of Siikajoki and Kalajoki, for example to Pyhäjoki. In that case, some of the wind farms of Raahe and Kalajoki area could be connected to the 400/100 kV substation of Pyhäjoki. However, the nuclear power plant that has been planned to Pyhäjoki affects the building of the substation [34]. In this thesis, it has been assumed that there is not 400/110 kV substation in Pyhäjoki and it is possible to connect 1525 MW wind power capacity to the substation of Siikajoki. The wind power networks of scenario 3 are shown in Figure 6.8.

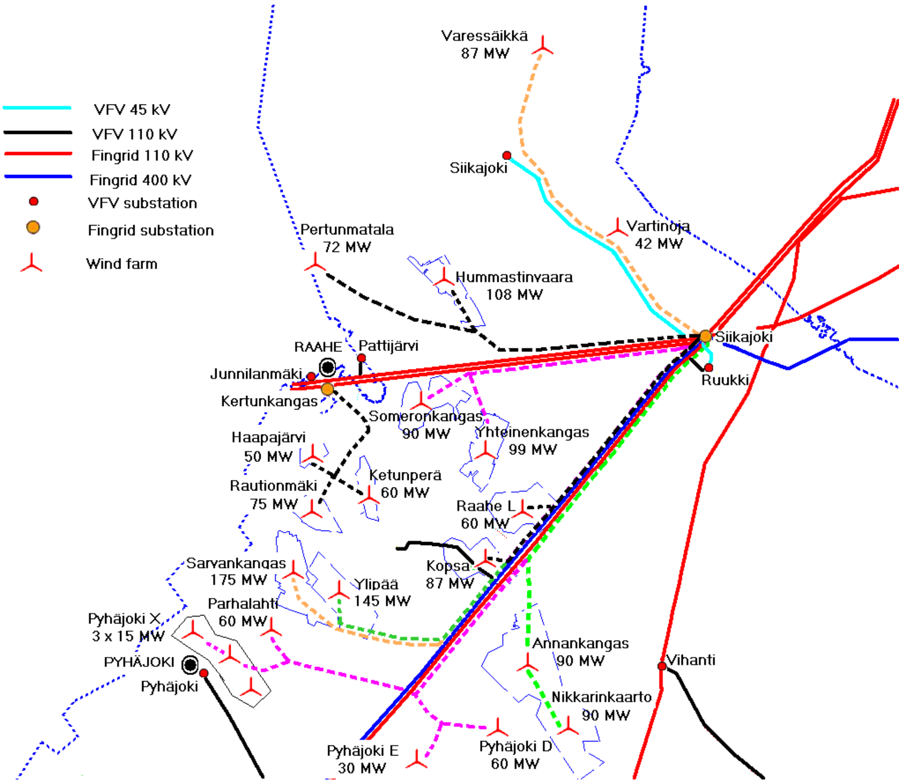


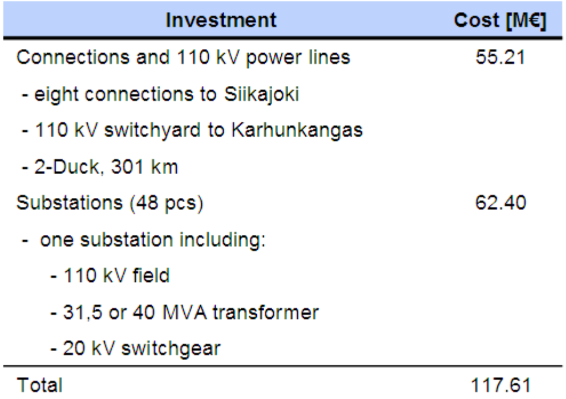
Figure 6.8 *Wind farms and wind power networks of scenario 3.*

Sarvankangas and Ylipää should be connected with their own power line to the substation of Siikajoki if the power of the wind farm altogether is more than 155 MW. In the scenario 3, it is assumed that the wind farms would be realized with their maximum wind power capacity.

Raahe L wind farm would be possible to connect the power line of Kopsa. Difference with regard to wind power networks of scenario 2, Hummastinvaara has been connected to Siikajoki with own power line in which case Pertunmatala could be connected to the same power line.

The wind farms of Pyhäjoki area could be connected to Siikajoki with one 2-Duck conductor but it would require the building of the power line structure on the nominal voltage 133 kV. When the wind farms operate with the maximum power, the voltage is more than 123 kV on the substation of wind farms if the voltage is the 118 kV in Siikajoki. The costs of the wind power networks are shown in Table 6.7.

Table 6.7 *Costs of wind power networks.*



Investment	Cost [M€]
Connections and 110 kV power lines	55.21
- eight connections to Siikajoki	
- 110 kV switchyard to Karhunkangas	
- 2-Duck, 301 km	
Substations (48 pcs)	62.40
- one substation including:	
- 110 kV field	
- 31,5 or 40 MVA transformer	
- 20 kV switchgear	
Total	117.61

Eight connections to the substation of Siikajoki would be needed and approximately more than 300 km of a power line. The estimated costs would be about 118 million euro including the substations of wind farms.

7. DEVELOPMENT PLAN

7.1. Nivala – Vuolijoki – Koivisto regional network

The longest power line of VFV is Koivisto – Nivala power line that reaches from Central Finland to Northern Ostrobothnia. The length of power line is about 220 km and ten substations have been connected to power line. The nominal power of the main transformers varies 10…25 MVA. The total power of the main transformers is about 200 MVA.

The power line has been connected to the main grid in the substations of Nivala, Vuolijoki and Koivisto. In the normal situation, it is fed from Nivala to Haapajärvi, from Koivisto to Pihtipudas and from Vuolijoki to Pyhäjärvi and Pyhäsalmi. Nivala – Vuolijoki – Koivisto power line and substations are introduced in Figure 7.1. Furthermore, the power lines of Fingrid and the other substations of VFV are shown in the figure.

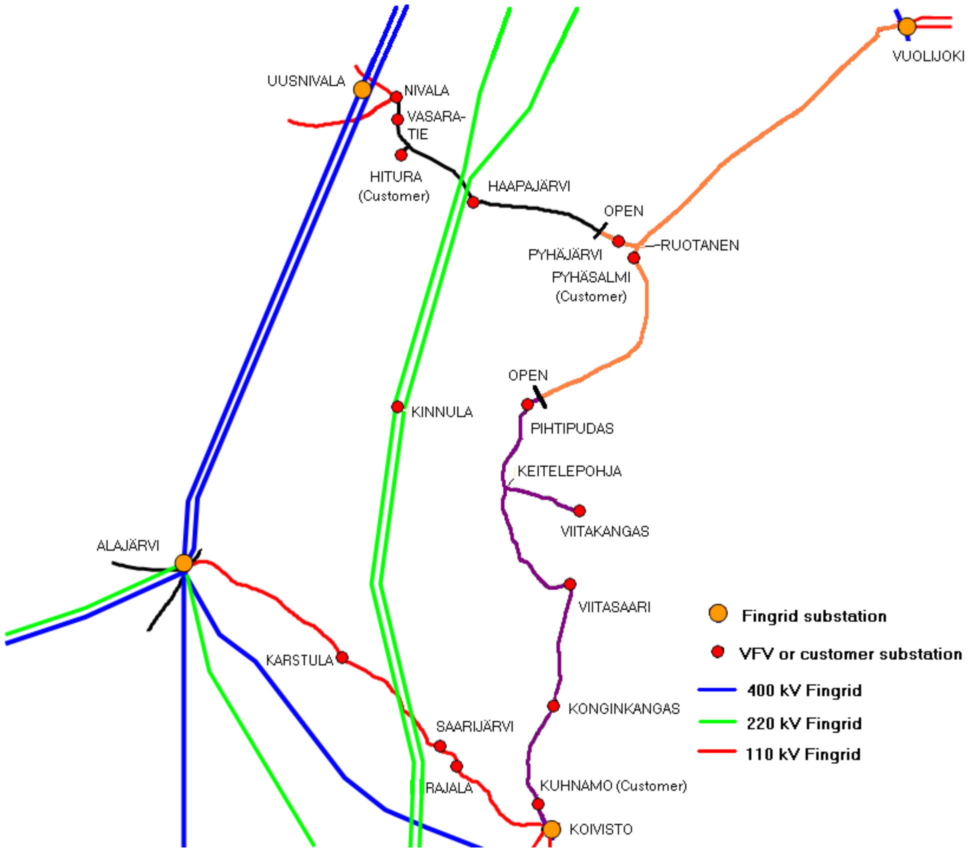


Figure 7.1 *Nivala – Vuolijoki – Koivisto power line and substations.*

In normal situation, it would be possible to feed the substations so that Vuolijoki – Ruotanen power line would not be in use and Pyhäjärvi and Pyhäsalmi would be fed from Nivala. However, the electricity supply of the area requires three separate connection points to the main grid in the backup feeding situation.

For example, if a fault takes place between Nivala and Vasaratie, the backup feeding of the power line does not succeed from Koivisto to Vasaratie during the present peak load (about 120 MW). In this case, the voltage would be below 50 kV in Vasaratie. Furthermore, the power lines would be more than in 130 % load between Koivisto and Viitasaari. The backup feeding does not succeed either from Nivala to Kuhnamo since the voltage would be below 90 kV in Kuhnamo and the power lines would be in over load between Nivala and Haapajärvi.

The reconstruction of the whole power line with the 2-Duck conductor would not help a situation because the voltage would be still about 95 kV in Vasaratie. Because of ageing and weak power lines of the area, two different alternatives to develop the network have been examined in the following chapters. The starting point is in the first alternative, that Vuolijoki – Ruotanen is still in use. In the second alternative, it is examined the network where Vuolijoki – Ruotanen is out of service and the third connection point to the main grid is on the substation of Uusnivala.

7.1.1. Alternative 1 – Reconstruction of existing power lines

As mentioned in last chapter, Vuolijoki – Ruotanen power line would not be needed in the normal situation but the power line is especially important in the backup feeding situations. However, there also are situations in the backup feeding in which case the transfer capacity of the present power line is not adequate. For example, if a fault takes place between Koivisto and Kuhnamo during the peak load, it is not possible to feed from Vuolijoki to Kuhnamo and Konginkangas. The backup feeding will not succeed from Vuolijoki to Vasaratie either.

Vuolijoki – Ruotanen power line should be reconstructed with 2-Duck conductor in order to the backup feeding would succeed to Konginkangas and Vasaratie. However, the reconstruction of the power line does not improve a situation sufficiently in order to backup feeding would succeed to Kuhnamo. Consequently, it would be reasonable to build the backup connection from Koivisto – Alajärvi power line to Kuhnamo.

The Nivala – Haapajärvi power line should be reconstruction before one of the 220 kV power lines is brought into 110 kV use. In that case, the substation of Kinnula could be fed from the substation of Nivala.

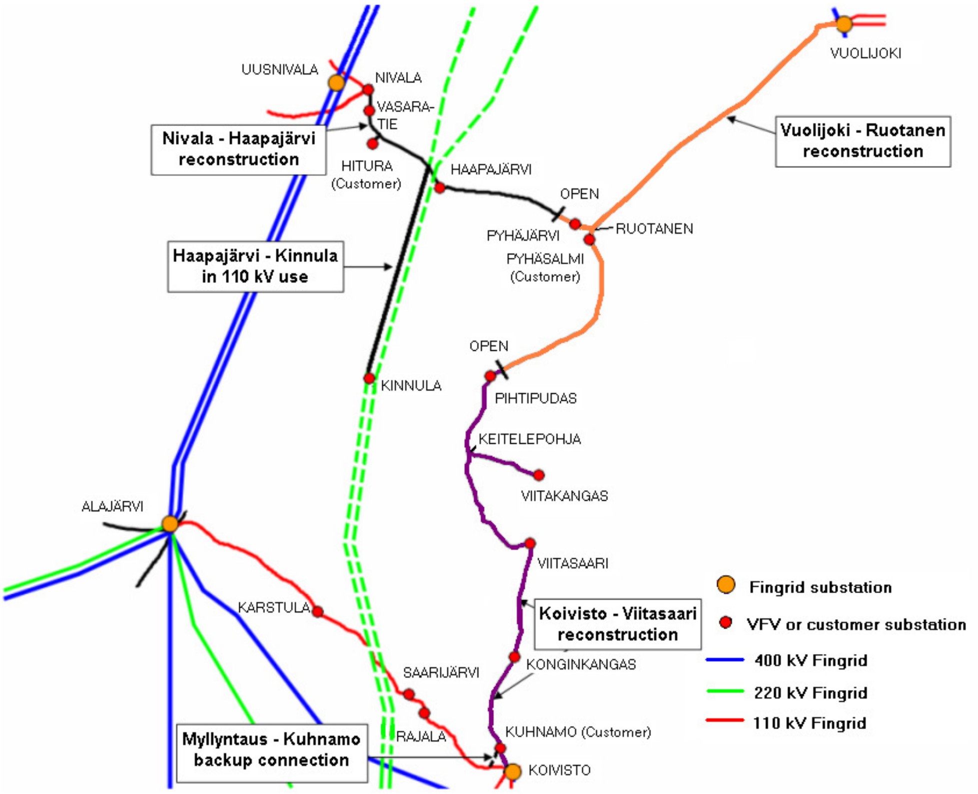


***Figure 7.2** Investments of the alternative 1.*

Investments of the alternative 1 are introduced in Figure 7.2. At first, Vuolijoki – Ruotanen power line should be reconstructed with 2-Duck conductor. Furthermore, the backup connection should be built from Koivisto – Alajärvi power line to Kuhnamo. The Nivala – Haapajärvi power line should be reconstructed before one of the 220 kV power lines is brought into 110 kV use. After this, the substation of Kinnula could be connected to the branch which is located near Haapajärvi and the substation could be fed from the substation of Nivala. The length of power line is about 50 km from Haapajärvi to Kinnula. At last, the Koivisto – Viitasaari power line should be reconstructed. The costs and estimated schedules of above mentioned investment are introduced in Table 7.1.

***Table 7.1** Costs of alternative 1.*

Investment	Cost [M€]	Year
Myllyntaus - Kuhnamo including:	0.44	2012 - 2013
- 110 kV power line, 3km		
- 110 kV line disconnector		
Vuolijoki - Ruotanen including:	10.01	2012 - 2015
- 110 kV power line, 72 km		
Nivala - Haapajärvi including:	3.46	2014 - 2016
- 110 kV power line, 30 km		
Koivisto - Viitasaari including:	6.37	2019 - 2022
- 110 kV power line, 55 km		
Total	20.28	

The total costs would be about 20 million euro. The total costs do not contain the cost of Haapajärvi – Kinnula power line. The estimated schedules are based on the assumption that one of 220 kV power lines will bring into 110 kV use during the year 2015.

7.1.2. Alternative 2 – New connection from Uusnivala

In this chapter, a new connection has been examined from Uusnivala to Keitelepohja in which case Vuolijoki – Ruotanen power line could be demolished. About 67 km of new power line should be built and cashed about 50 km of Haapajärvi – Kinnula power line. The costs of Haapajärvi – Kinnula power line have not been taken into consideration in the total costs, such as it was not taken into consideration when examining alternative 1. The investments of alternative 2 are introduced in Figure 7.3.

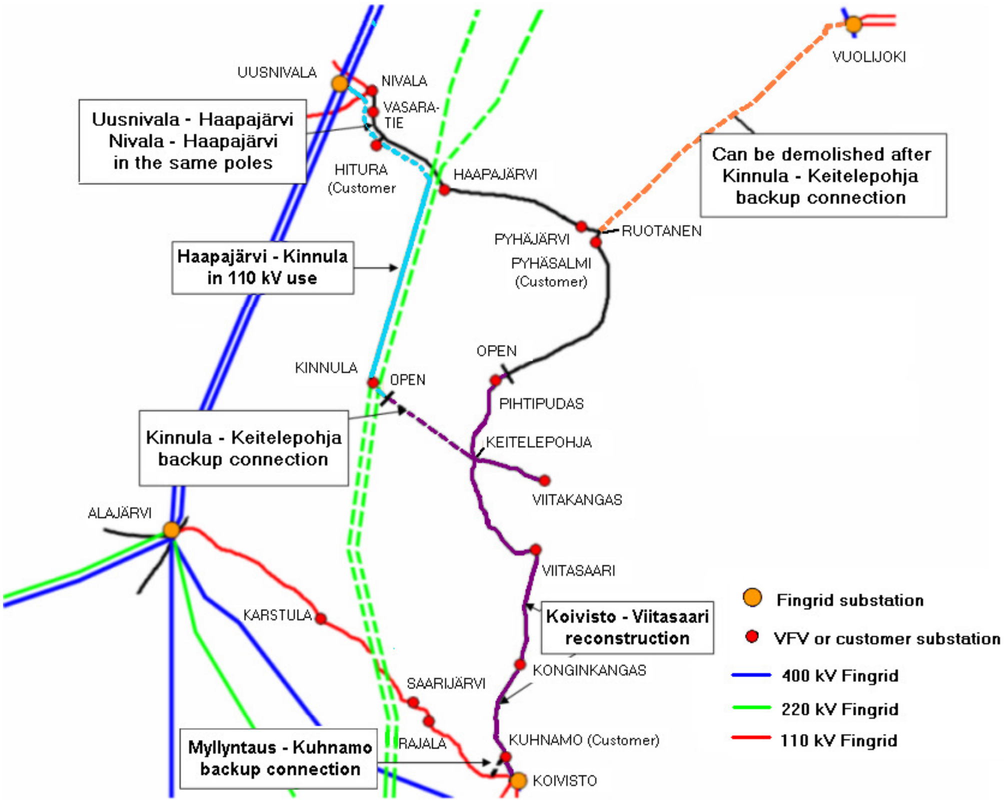


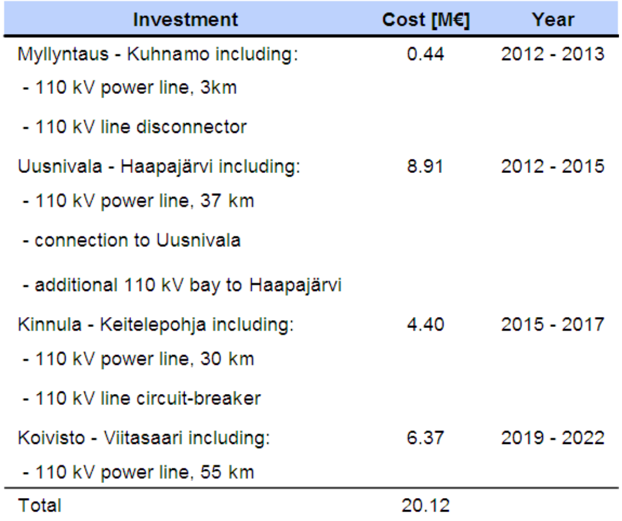
Figure 7.3 *Vuolijoki-Ruotanen power line demolished and new power line from Uusnivala to Keitelepohja. Normal connection situation.*

The new circuit would be built from Uusnivala to Keitelepohja so that 37 km from Uusnivala to Haapajärvi would be 2-Duck conductor and 30km from Kinnula to Keitelepohja would be Duck conductor. Furthermore, one of the Fingrid's 220 kV power lines would be brought into 110 kV use. The conductors of 220 kV power lines are Condor and Finch. The electrical examinations have been made with the Condor conductor.

The Nivala – Haapajärvi power line should be reconstructed with Duck conductor at the same time if the power line were built from Uusnivala to Keitelepohja. In that case, the power lines could be built to the same poles. Furthermore, both power lines would be worth connection to the substation of Vasaratie, Hitura and Haapajärvi so that connection situation could be changed depending on the loads of substations. For example, if only the substation of Kinnula would be connected to the power line which leaves Uusnivala, the power line would produce reactive power to the main grid on light load. Thus, Haapajärvi, Pyhäjärvi and Pyhäsalmi would be worth connecting to Uusnivala – Kinnula power line.

After Kinnula – Keitelepohja power line, it would be possible to demolish Vuolijoki – Ruotanen power line, because it could be fed from Uusnivala to Konginkangas. However, the backup feeding does not succeed to Kuhnamo during the peak load so it would be reasonable to build the backup connection from Koivisto – Alajärvi power line to Kuhnamo. Furthermore, the Koivisto – Viitasaari power line should be reconstructed. The costs and estimated schedules of investment are introduced in Table 7.2.

Table 7.2 *Cost of alternative 2*



Investment	Cost [M€]	Year
Myllyntaus - Kuhnamo including:	0.44	2012 - 2013
- 110 kV power line, 3km		
- 110 kV line disconnector		
Uusnivala - Haapajärvi including:	8.91	2012 - 2015
- 110 kV power line, 37 km		
- connection to Uusnivala		
- additional 110 kV bay to Haapajärvi		
Kinnula - Keitelepohja including:	4.40	2015 - 2017
- 110 kV power line, 30 km		
- 110 kV line circuit-breaker		
Koivisto - Viitasaari including:	6.37	2019 - 2022
- 110 kV power line, 55 km		
Total	20.12	

Merely on the basis of the investment costs, alternative 2 would be about 160 000 euro cheaper than alternative 1. When attention is paid to the lifespan costs of alternatives, alternative 1 would be about 880 000 euro cheaper than alternative 2 (Figure 7.4). Alternative 2 would be more expensive since the probable interruption costs of the network would be bigger than alternative 1. Interruption costs have been calculated on a fault frequency that has been presented in Chapter 3.3 (Reliability). Furthermore, the prices of EMV have been used to the interruptions. [35]

However, alternative 2 would be better than alternative 1 electrotechnically. In backup feeding situation, voltage would be about 108 kV in Konginkangas in the year 2025, if it would be fed from Uusnivala, whereas, when it would be replaced from Vuolijoki, the voltage would be 105 kV.

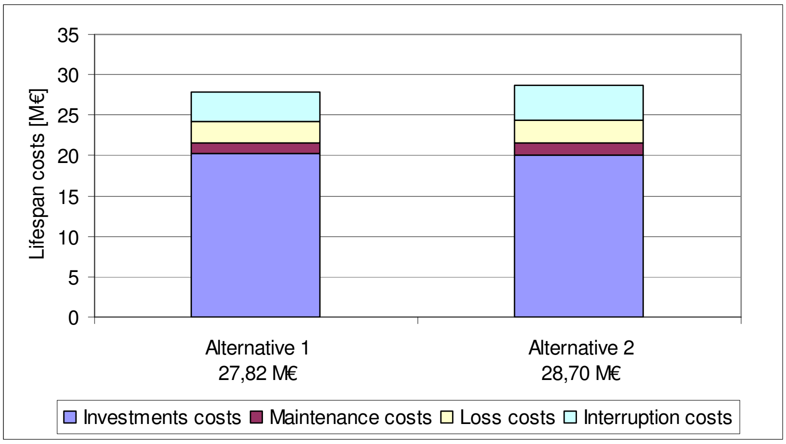


Figure 7.4 *Lifespan costs of alternatives. Money rate 7 %, load growth 2 % per year, loss cost 40€/MWh and observation period 40 years.*

7.2. Backup connection of Haapavesi and Pulkkila

Irrespective of which one of the 220 kV power lines will be brought into 110 kV use, it would be possible to utilize the power lines also for the backup connection of Haapavesi and Pulkkila. However, the connecting of the backup connection to Nivala – Haapajärvi power line requires that the power line has been reconstructed before. If the alternative 2 of Chapter 7.1 was carried out, it would be reasonable to connect the backup connection to Uusnivala – Haapajärvi power line due to the stronger conductor.

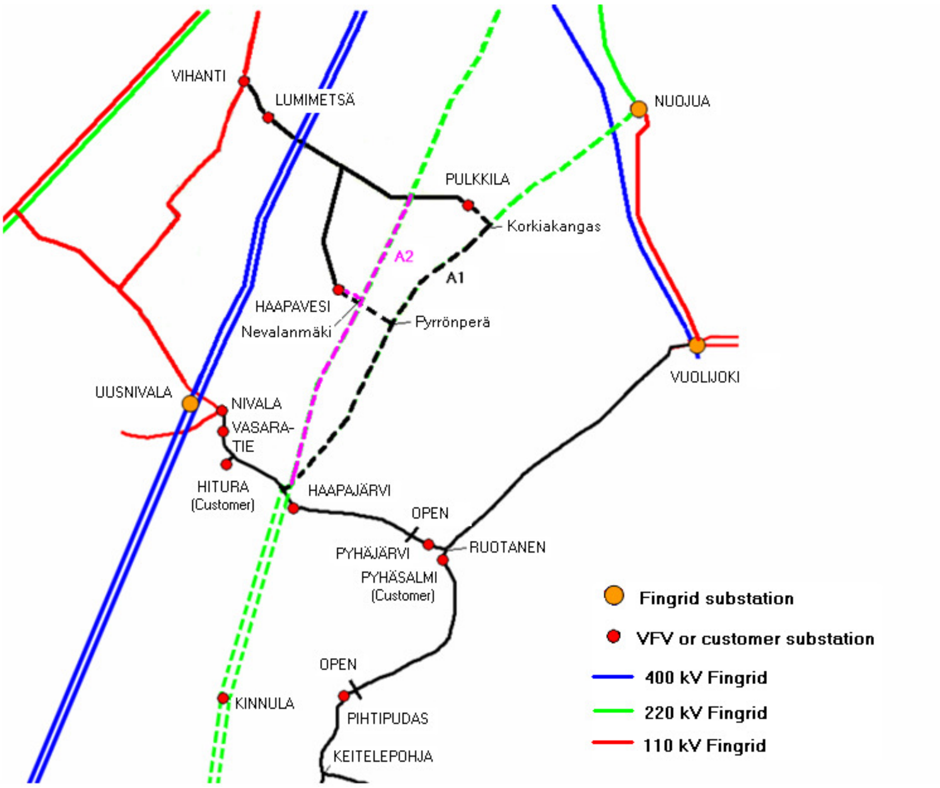


Figure 7.4 *Alternatives A1 and A2 for Haapavesi and Pulkkila backup connection.*

Figure 7.4 shows the alternatives A1 and A2 for the backup connection of Haapavesi and Pulkkila. The A1 has been described on a black dash line and the A2 on a violet dash line. If Petäjävesi – Nuojua power line is brought into 110 kV use (a black dash line), it could be built from the branch of Pyrrönperä to Haapavesi about 20 km of the power line and from the branch of Korkiakangas to Pulkkila about 6 km of the power line. Correspondingly, if Petäjävesi – Pyhäkoski power line is brought into 110 kV use (a violet dash line), it could be built from the branch of Nevalanmäki to Haapavesi about 6 km of the power line. A new power line would not need to be built to Pulkkila due to Petäjävesi – Pyhäkoski power line goes over the present 110 kV power line. The costs of different alternatives are shown in Table 7.3.

Table 7.3 *Costs of different alternatives.*

Investment	Cost [M€]
Alternative A1 including:	4.10
- Pyrrönperä - Haapavesi, 20 km	
- Korkiakangas - Pulkkila, 6 km	
- two line circuit-breaker	
Alternative A2 including:	1.34
- Nevalanmäki - Haapavesi, 6 km	
- two line circuit-breaker	
Nivala – Haapavesi 110 kV, 30 km	4.20

Cost caused by cashing of Fingrid's power line has not been taken into consideration in the costs of alternatives A1 and A2. Because of a comparison, the costs of Nivala – Haapavesi 110 kV power line are also shown in the table. The costs of Nivala – Haapavesi power line have been calculated if new 110 kV power line is built to the place of the present 45 kV power line. The cheapest alternative is the A2 without the costs of Fingrid's power line.

7.3. Tikinmaa – Forssa regional network

As stated in Chapter 5.3.1 (load growth), Tikinmaa – Toijala and Humppila – Huhtia power lines will be overloaded in backup feeding situation in the year 2025 if load growth is 2 % per year. Therefore, power lines should be reconstructed during the coming years. Furthermore, the mechanical condition of Toijala – Urjala and Urjala – Humppila power lines are weak so these power lines should also reconstruct during the next ten years.

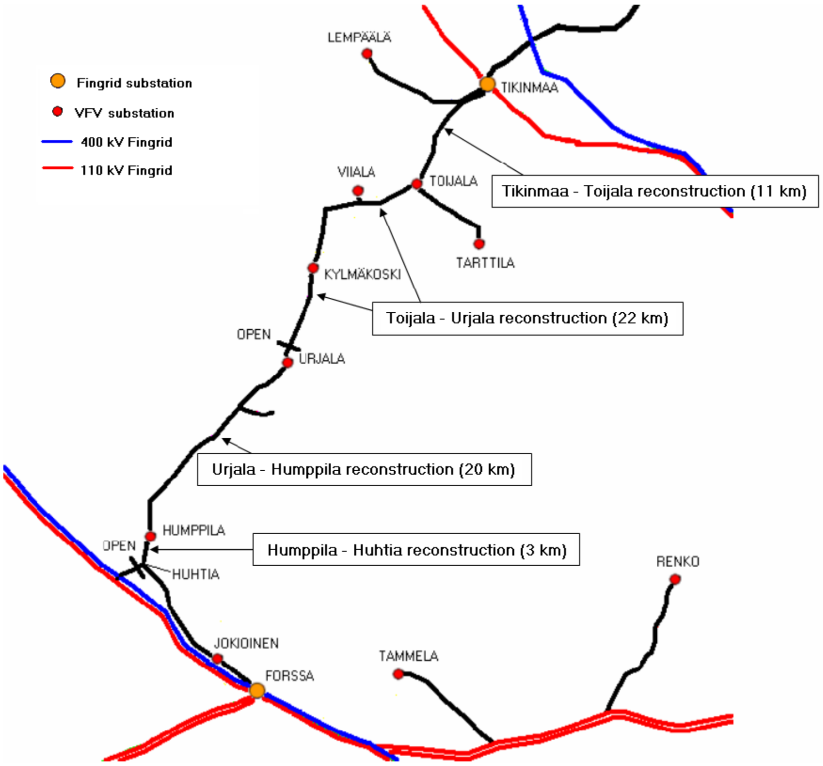


Figure 7.4 *Tikinmaa – Forssa regional network.*

Tikinmaa – Forssa regional network are introduced in Figure 7.4. As a first of the power lines, about 11 km long Tikinmaa – Toijala and about 3 km long Humppila – Huhtia power lines should be reconstructed in order to the power lines are not overloaded in the backup feeding situations (Appendix 4). Due to mechanical condition and voltage drop on the substation of Tarttila in backup feeding situation, Urjala – Humppila power line should be as the following. Toijala – Urjala power line should also be reconstructed for the same reason as Urjala – Humppila power line.

The investment costs and schedules for Tikinmaa – Forssa regional network are shown in Table 7.4. The estimated schedules will be based on the overloading and voltage drop of the power lines in the backup feeding situations when the loads increase by 2 % per year.

Table 7.4 *Investment costs and schedules.*

Investment	Cost [M€]	Year
Tikinmaa - Toijala including: - 110 kV power line, 11km	1.27	2015 - 2017
Huhtia - Humppila including: - 110 kV power line, 3km	0.35	2015 - 2017
Urjala - Humppila including: - 110 kV power line, 20 km	2.32	2021 - 2023
Toijala - Urjala including: - 110 kV power line, 22 km	2.55	2023 - 2025
Total	6.49	

7.4. Summary of development plan

The change in the voltage level of 220 kV power lines affects the development plan of the regional network widely in Central Finland and Northern Ostrobothnia. Due to the factors which are independent of VFV, the timing of investments is difficult. However, it has been assumed in the timing that the 220 kV power lines will bring into 110 kV use during the year 2015.

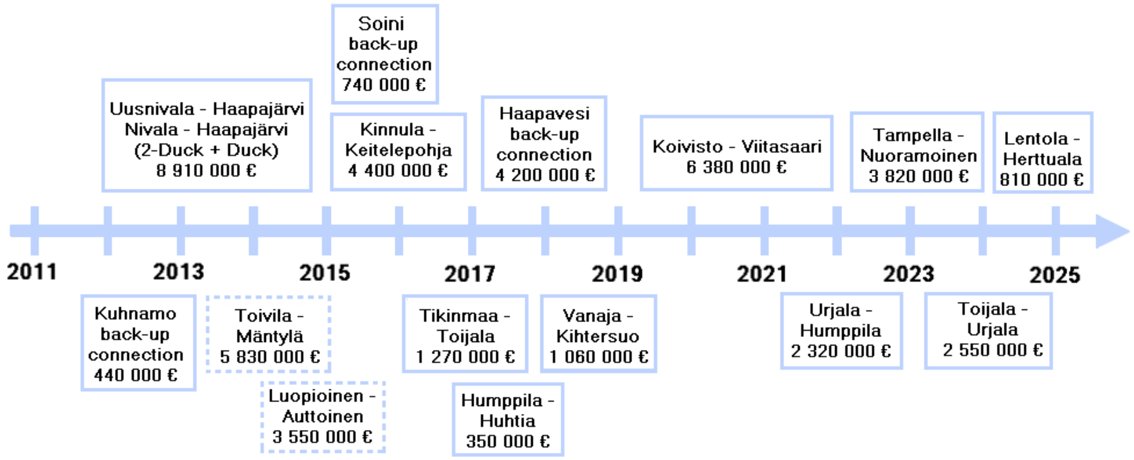


Figure 7.5 *Investments and their schedules until the year 2025.*

Investments and their schedules are shown in Figure 7.5 until the year 2025. The starting point is that the new connection would be built from Uusnivala to Keitelepohja, in spite of the fact that, it would become about 880 000 euro more expensive than the reconstruction of the present power lines on the basis of the lifespan costs. The reason is that the new connection would be more long-lived electrotechnically when the load growths of the substations are taken into consideration.

As a first, it would be invested in the backup connection of Kuhnamo and new connection from Uusnivala to Haapajärvi in which case the Nivala – Haapajärvi power line would be reconstructed at the same time. Furthermore, Tikinmaa – Mäntylä and Luopioinen – Auttoinen backup connections should be examined in more detail. Toivila – Mäntylä and Luopioinen – Auttoinen investments have been described on the dash lines since the investments of the regional network are not needed if some other solutions are found. In this thesis, only 110 kV connections have been examined as solutions.

Near the year 2015, if the 220 kV power lines bring into 110 kV use, Kinnula – Keitelepohja power line should be built. At the same time, Vuolijoki – Ruotanen power line could be demolished since the substations, which are fed from Koivisto, would be able to feed from Uusnivala. Furthermore, it would be possible to build the backup connections to the substation of Soini and Haapavesi utilising the present 220 kV power lines of the main grid.

Halfway through the observation period, the Tikinmaa – Toijala and Humppila – Huhtia power lines should be reconstructed. Together with the investments of the main grid, it would be possible to build Vanaja – Kihtersuo connection in which case the substations of Hämeenlinna could be fed in loop.

At the end of the observation period, the Koivisto – Viitasaari, Urjala – Humppila and Toijala – Urjala power lines should be reconstructed. The power lines are mechanically in weak condition, in addition, if the loads increase according to prediction, the power lines are also overloaded in the backup feeding situations. Furthermore, Tampella – Nuoramoinen and Lentola – Herttuala power lines should be reconstructed since they are the oldest power lines of the regional network.

In summary, if the above mentioned investments are carried out, VFV should reconstruct the present power lines about 200 km and build new power lines about 150 km during the next fifteen years. Furthermore, about 100 km of Fingrid's power lines should be cashed. The money should be reserved about 45 million euro for investments.

8. CONCLUSIONS

The purpose of this thesis was to create a development plan for 110 kV regional network of Vattenfall Verkko Ltd. The starting point for the thesis was to model the regional network with the PSS/E software in order to it was possible to determine the electrical and mechanical condition of the network. On the basis of the condition information, the existing power lines should be significantly reconstruction in the coming years. Furthermore, the new 110 kV power lines should be built when taking into consideration the change factors which affect the regional network.

The loads growth, the development plans of the main grid and wind power production were examined as the most important change factors. In the future, the biggest change factors are 220 kV power lines of the main grid changing into 110 kV use in Central Finland and Northern Ostrobothnia and also wind farms increase in Northern Ostrobothnia. The increase in 110 kV power lines makes the building of the new connections and substations possible.

Considering the plans of the main grid and loads growth, two alternative solutions for the longest Koivisto – Nivala power line were examined and their possibilities for implementation were clarified. Furthermore, wind power projects were examined in three different scenarios and were created for wind power networks at basic level.

As a final result, the investment proposal, which is presented in Chapter 7.4, was created until the year 2025. On the basis of the investment proposal, the network company can provide for the future investment needs. The modelled regional network, which can be utilised in everyday operation, can be considered also as one result of the thesis.

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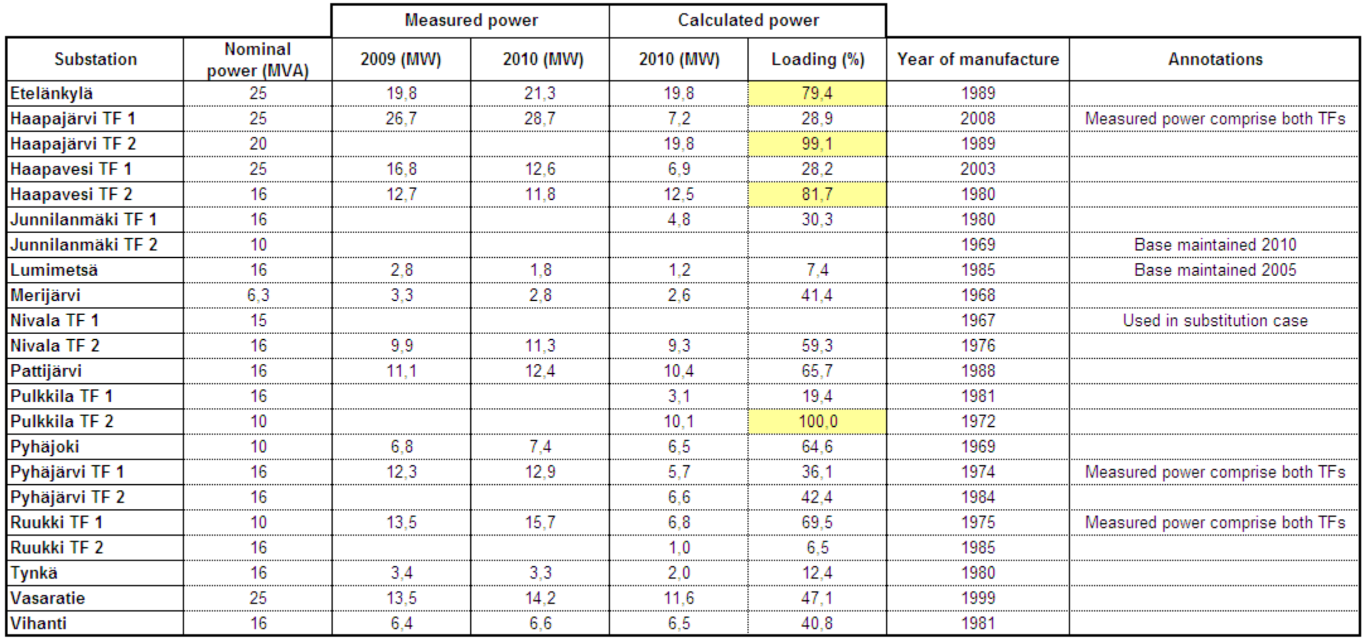
APPENDIX

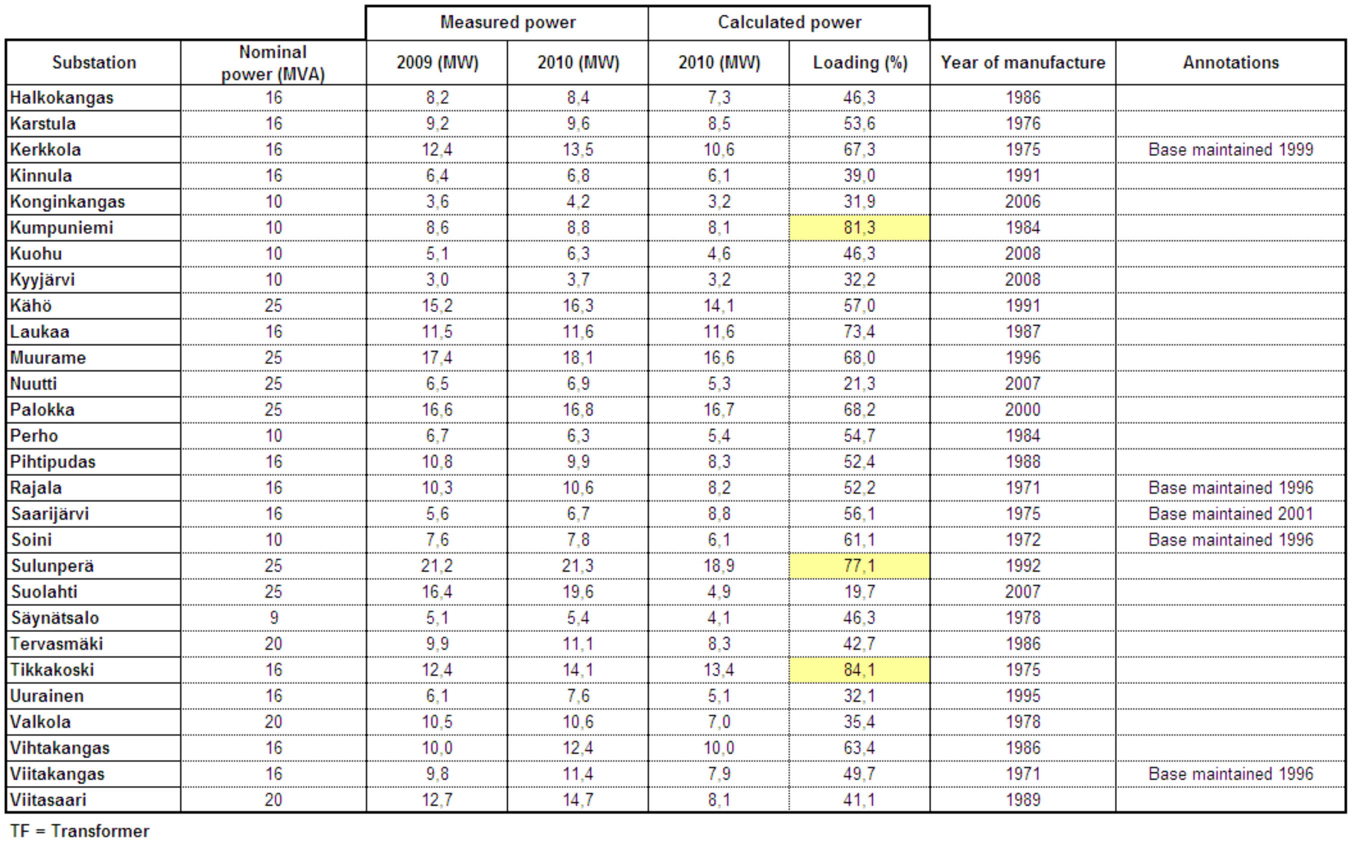
APPENDIX 1 – NORTHERN OSTROBOTHNIA: MEASURED AND CALCULATED POWERS OF THE MAIN TRANSFORMERS



Substation	Nominal power (MVA)	Measured power		Calculated power		Year of manufacture	Annotations
		2009 (MW)	2010 (MW)	2010 (MW)	Loading (%)		
Etelänkylä	25	19,8	21,3	19,8	79,4	1989	
Haapajärvi TF 1	25	26,7	28,7	7,2	28,9	2008	Measured power comprise both TFs
Haapajärvi TF 2	20			19,8	99,1	1989	
Haapavesi TF 1	25	16,8	12,6	6,9	28,2	2003	
Haapavesi TF 2	16	12,7	11,8	12,5	81,7	1980	
Junnilanmäki TF 1	16			4,8	30,3	1980	
Junnilanmäki TF 2	10					1969	Base maintained 2010
Lumimetsä	16	2,8	1,8	1,2	7,4	1985	Base maintained 2005
Merijärvi	6,3	3,3	2,8	2,6	41,4	1968	
Nivala TF 1	15					1967	Used in substitution case
Nivala TF 2	16	9,9	11,3	9,3	59,3	1976	
Pattijärvi	16	11,1	12,4	10,4	65,7	1988	
Pulkkila TF 1	16			3,1	19,4	1981	
Pulkkila TF 2	10			10,1	100,0	1972	
Pyhäjoki	10	6,8	7,4	6,5	64,6	1969	
Pyhäjärvi TF 1	16	12,3	12,9	5,7	36,1	1974	Measured power comprise both TFs
Pyhäjärvi TF 2	16			6,6	42,4	1984	
Ruukki TF 1	10	13,5	15,7	6,8	69,5	1975	Measured power comprise both TFs
Ruukki TF 2	16			1,0	6,5	1985	
Tynkä	16	3,4	3,3	2,0	12,4	1980	
Vasaratie	25	13,5	14,2	11,6	47,1	1999	
Vihanti	16	6,4	6,6	6,5	40,8	1981	

TF = Transformer

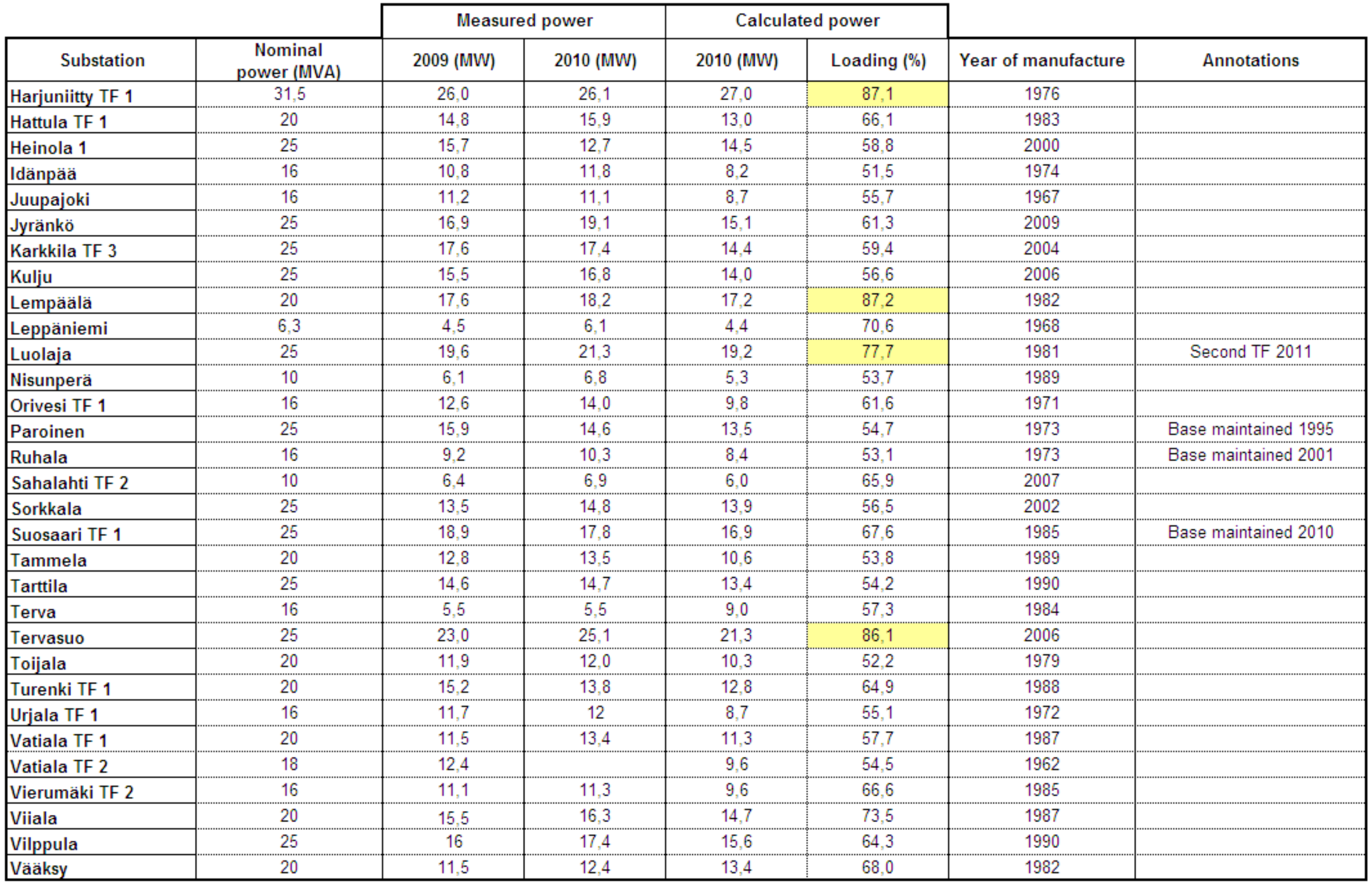
APPENDIX 2 – CENTRAL FINLAND: MEASURED AND CALCULATED POWERS OF THE MAIN TRANSFORMERS



Substation	Nominal power (MVA)	Measured power 2009 (MW)	Measured power 2010 (MW)	Calculated power 2010 (MW)	Calculated power Loading (%)	Year of manufacture	Annotations
Halkokangas	16	8,2	8,4	7,3	46,3	1986	
Karstula	16	9,2	9,6	8,5	53,6	1976	
Kerkkola	16	12,4	13,5	10,6	67,3	1975	Base maintained 1999
Kinnula	16	6,4	6,8	6,1	39,0	1991	
Konginkangas	10	3,6	4,2	3,2	31,9	2006	
Kumpuniemi	10	8,6	8,8	8,1	81,3	1984	
Kuohu	10	5,1	6,3	4,6	46,3	2008	
Kyyjärvi	10	3,0	3,7	3,2	32,2	2008	
Kähö	25	15,2	16,3	14,1	57,0	1991	
Laukaa	16	11,5	11,6	11,6	73,4	1987	
Muurame	25	17,4	18,1	16,6	68,0	1996	
Nuutti	25	6,5	6,9	5,3	21,3	2007	
Palokka	25	16,6	16,8	16,7	68,2	2000	
Perho	10	6,7	6,3	5,4	54,7	1984	
Pihtipudas	16	10,8	9,9	8,3	52,4	1988	
Rajala	16	10,3	10,6	8,2	52,2	1971	Base maintained 1996
Saarijärvi	16	5,6	6,7	8,8	56,1	1975	Base maintained 2001
Soini	10	7,6	7,8	6,1	61,1	1972	Base maintained 1996
Sulunperä	25	21,2	21,3	18,9	77,1	1992	
Suolahti	25	16,4	19,6	4,9	19,7	2007	
Säynätsalo	9	5,1	5,4	4,1	46,3	1978	
Tervasmäki	20	9,9	11,1	8,3	42,7	1986	
Tikkakoski	16	12,4	14,1	13,4	84,1	1975	
Uurainen	16	6,1	7,6	5,1	32,1	1995	
Valkola	20	10,5	10,6	7,0	35,4	1978	
Vihtakangas	16	10,0	12,4	10,0	63,4	1986	
Viitakangas	16	9,8	11,4	7,9	49,7	1971	Base maintained 1996
Viitasaari	20	12,7	14,7	8,1	41,1	1989	

TF = Transformer

APPENDIX 3 – HÄME AND PIRKANMAA: MEASURED AND CALCULATED POWERS OF THE MAIN TRANSFORMERS



Substation	Nominal power (MVA)	Measured power		Calculated power		Year of manufacture	Annotations
		2009 (MW)	2010 (MW)	2010 (MW)	Loading (%)		
Harjuniitty TF 1	31,5	26,0	26,1	27,0	87,1	1976	
Hattula TF 1	20	14,8	15,9	13,0	66,1	1983	
Heinola 1	25	15,7	12,7	14,5	58,8	2000	
Idänpää	16	10,8	11,8	8,2	51,5	1974	
Juupajoki	16	11,2	11,1	8,7	55,7	1967	
Jyränkö	25	16,9	19,1	15,1	61,3	2009	
Karkkila TF 3	25	17,6	17,4	14,4	59,4	2004	
Kulju	25	15,5	16,8	14,0	56,6	2006	
Lempäälä	20	17,6	18,2	17,2	87,2	1982	
Leppäniemi	6,3	4,5	6,1	4,4	70,6	1968	
Luolaja	25	19,6	21,3	19,2	77,7	1981	Second TF 2011
Nisunperä	10	6,1	6,8	5,3	53,7	1989	
Orivesi TF 1	16	12,6	14,0	9,8	61,6	1971	
Paroinen	25	15,9	14,6	13,5	54,7	1973	Base maintained 1995
Ruhala	16	9,2	10,3	8,4	53,1	1973	Base maintained 2001
Sahalahti TF 2	10	6,4	6,9	6,0	65,9	2007	
Sorkkala	25	13,5	14,8	13,9	56,5	2002	
Suosaari TF 1	25	18,9	17,8	16,9	67,6	1985	Base maintained 2010
Tammela	20	12,8	13,5	10,6	53,8	1989	
Tarttila	25	14,6	14,7	13,4	54,2	1990	
Terva	16	5,5	5,5	9,0	57,3	1984	
Tervasuo	25	23,0	25,1	21,3	86,1	2006	
Toijala	20	11,9	12,0	10,3	52,2	1979	
Turenki TF 1	20	15,2	13,8	12,8	64,9	1988	
Urjala TF 1	16	11,7	12	8,7	55,1	1972	
Vatiala TF 1	20	11,5	13,4	11,3	57,7	1987	
Vatiala TF 2	18	12,4		9,6	54,5	1962	
Vierumäki TF 2	16	11,1	11,3	9,6	66,6	1985	
Viiala	20	15,5	16,3	14,7	73,5	1987	
Vilppula	25	16	17,4	15,6	64,3	1990	
Vääksy	20	11,5	12,4	13,4	68,0	1982	

TF = Transformer

APPENDIX 4 – LOADINGS OF THE POWER LINES

Power line	Length (km)	Year of construction	Conductor	Loading 2010 (normal situation)	Loading 2010 (backup feed situation)	Loading 2025 (normal situation)	Loading 2025 (backup feed situation)
Vuolijoki - Ruotanen	72	1962	Ostrich	115 A / 21 %	442 A / 81 %	120 A / 24 %	697 A / 123 %
Tampella - Nuoramoinen	33	1965	Vaasa	154 A / 35 %		209 A / 47 &	
Nivala - Vasaratie	5	1967	Ostrich	227 A / 49 %		279 A / 60 %	
Vasaratie - Hitura	6	1967	Ostrich	172 A / 31 %		203 A / 37 %	
Hitura - Haapajärvi	19	1967	Ostrich	141 A / 26 %		172 A / 31 %	
Tikinmaa - Toijala	12	1968	Ostrich	273 A / 50 %	481 A / 88 %	360 A / 66 %	645 A / 118 %
Toijala - Urjala	22	1972	Ostrich	148 A / 27 %	355 A / 65 %	189 A / 35 %	472 A / 86 %
Koivisto - Kuhnamo	5	1973	Ostrich	303 A / 56 %		397 A / 73 %	
Kuhnamo - Viitasaari	55	1973	Ostrich	212 A / 39 %		303 A / 56 %	
Urjala - Humppila	20	1979	Ostrich	106 A / 19 %	404 A / 74 %	139 A / 25 %	550 A / 101 %
Humppila - Huhtia	3	1979	Ostrich	156 A / 29 %	454 A / 83 %	207 A / 38 %	620 A / 115 %